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Air Quality Assessment of Particulate Emissions from Diesel-Powered Vehicles

PEDCo-Environmental, Inc, Cincinnati, OH

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16. ABSTRACT

The report presents estimates of the impact projected diesel-powered vehicle sales will have on the levels of total suspended particulates (TSP) and benzo(a)pyrene (BaP) to which the population is exposed. A detailed particulate emission inventory is developed for a representative test city (Kansas City, MO) for a base year (1974). Emissions & population exposure to TSP & BaP are projected for 1981, 1983, 1985, & 1990. Emissions from all sources except diesel are assumed to remain constant in order that the full impact of diesels can be seen & because insufficient time was available to vary the model. An abbreviated discussion of possible health effects attributable to organic emissions from diesel powered vehicles is included.

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CONTENTS

	Page
LIST OF FIGURES	v
LIST OF TABLES	vi
LIST OF ABBREVIATIONS AND SYMBOLS	ix
ACKNOWLEDGMENT	xii
1.0 SUMMARY	1-1
2.0 INTRODUCTION	2-1
3.0 CHARACTERIZATION AND HEALTH EFFECTS ASSESSMENT OF DIESEL PARTICULATE EMISSIONS	3-1
3.1 Particulates	3-2
3.2 Polycyclic Organic Matter	3-17
3.3 Sulfates	3-27
3.4 Minor Components	3-30
3.5 Current Research Status	3-30
4.0 TEST CITY METHODOLOGY AND PROJECTIONS	4-1
4.1 Nonmotor Vehicle Emissions	4-6
4.2 Motor Vehicle Exhaust Emissions	4-11
4.3 Projected Impact of Diesel Emissions on Air Quality	4-34
4.4 Assessing Population Exposure	4-37
5.0 ESTIMATES OF POPULATION EXPOSURE TO TSP AND BaP	5-1

CONTENTS (continued)

Page

5.1 National Population Impact 5-1

5.2 Projected Maximum Impact of Diesel Emissions on Air Quality 5-20

5.3 Discussing Exposure Data 5-28

APPENDIX A A-1

APPENDIX B B-1

FIGURES

Number		Page
3-1	Particle Size Distribution	3-10
3-2	Impact of Vehicle Exhaust on Ambient Particulate Size Distribution Data for Gasoline-Powered Vehicles	3-13
3-3	Particle Size Deposition Probablities	3-15
4-1	The Test City Study Area - Kansas City, Missouri	4-3
4-2	Projected Heavy-duty Vehicle Sales	4-14
4-3	Procedures for calculating projection Years' Grid VMT by Vehicle Category for Two Diesel Introduction Rate Assumptions	4-17
4-4	Dosage Spectrum Distribution in the Tri-State Region	4-42
5-1	Correlation of Average NASN Annual Geometric Mean TSP Levels for Selected SMSA's Versus SMSA Population and Population Density	5-4
5-2	Information Flow Diagram for the Development of the Population TSP Dose Relationship for Each Projection Case	5-9

TABLES

Number		Page
1-1	Exhaust Emissions of TSP and BaP, Gasoline-Versus Diesel-Powered Vehicles	1-2
1-2	Diesel Share of New Sales by Model Year	1-2
1-3	Projected Motor Vehicle Particulate Exhaust Emissions for Kansas City	1-8
1-4	Predicted Peak Levels of Diesel-Generated TSP for Kansas City	1-9
1-5	Estimated Population Exposure to More Than the Federal Standard for TSP	1-11
3-1	Particulate Emissions from Diesel Versus Gasoline Passenger Cars	3-3
3-2	Elemental and Trace Metal Composition of Diesel Exhaust Particulates	3-5
3-3	Aerodynamic Diameters of Diesel Exhaust Particulates Collected in Various Stages of an Anderson Sampler	3-9
3-4	Diesel Exhaust Particle Size	3-11
3-5	Frequency of Occurrence of Formulas for Carcinogenic Compounds in Diesel Exhaust Particulates	3-18
3-6	Compounds Detected in Various Atmospheric Pollutants (G), (D), and (A) Samples	3-20
3-7	Benzo[a]pyrene Emissions from Diesel Versus Gasoline Cars	3-22
3-8	Sulfate Emissions from Diesel Versus Gasoline Passenger Cars	3-29

TABLES (continued)

Number		Page
4-1	Particulate Emissions in Test City	4-7
4-2	Comparison of Measured Versus Predicted TSP Concentrations, Kansas City	4-9
4-3	Base-Year Fractions of Total Vehicles in Use Nationwide	4-19
4-4	Base-Year Fractions of Total Heavy-Duty Trucks in Use Nationwide (and Diesel Fractions Thereof)	4-21
4-5	Classification of Trucks by GVM	4-22
4-6	Truck Sales and Diesel Penetration Fractions	4-24
4-7	Diesel Vehicle Introduction Rates	4-26
4-8	Fraction of Urban VMT by Mobile Source Category in Projection Years	4-27
4-9	Exhaust Emission Factors	4-29
4-10	Weighted Emission Factors for Gasoline-Powered Vehicles	4-31
4-11	Projected Motor Vehicle Exhaust Emissions (Particulate)	4-32
4-12	Projected Motor Vehicle Exhaust Emissions (BaP)	4-33
4-13	Ratio of BaP to Particulate Emissions (Diesels Only)	4-35
4-14	Projected Regional Annual Average Concentrations of TSP from Diesel Exhaust for Test City	4-36
4-15	Projected Regional Annual Average Concentrations of BaP from Diesel Exhaust for Test City	4-38

TABLES (continued)

Number		Page
5-1	Distribution of U.S. Population by SMSA Population Range and Population Density for Projection Years - National SMSA Populations	5-5
5-2	Summary of TSP Data from Test City Monitoring Stations	5-7
5-3	Estimated Annual Exposure Concentrations of TSP From Diesel Vehicle Exhaust	5-10
5-4	Percent of Population Exposure to TSP Attributable to Diesel Exhaust Emissions	5-11
5-5	Estimated Population Exposed to More Than the Federal Standard for TSP	5-13
5-6	Annual Average Exposure Concentratios of BaP Emitted by Coke Ovens	5-16
5-7	Annual Average Ambient BaP Concentrations at NASN Urban Stations Without Coke Oven Impact	5-17
5-8	Population Exposure to BaP in Urban Areas Without Coke Oven Impact	5-18
5-9	Estimated Total Population Dosage of BaP in 1976	5-21
5-10	Annual Average Exposure Concentrations of BaP From Diesel Exhaust Emissions	5-22
5-11	Projected Concentrations of TSP from Diesel Exhaust	5-24
5-12	Projected Maximum Concentrations of BaP From Diesels	5-29
A-1	Fractions of Light-Duty Vehicle VMT in Projection Years	A-2
A-2	Fractions of Light-Duty Trucks VMT in Projection Years	A-3
A-3	Fractions of Heavy-Duty Truck VMT for Projections Years, Urban Only	A-4
B-1	Average SMSA TSP Levels Correlated with Population Parameters	A-5

LIST OF ABBREVIATIONS AND SYMBOLS

The following is an alphabetical list of terms used in the report.

Ao - land area used in estimating population dose.

ADT - annual daily traffic volume.

AQDM - Air Quality Dispersion Model.

BaP - benzo[a]pyrene.

Best est. - best estimate of light and heavy diesel vehicle growth trends.

C - average contribution of paved roads to measured TSP level, μg/m^3.

C max. - maximum pollutant concentration expected for a time period of concern.

$\bar{D}$ - dosage threshold used to estimate a dosage spectrum S ($\bar{D}$).

FHWA - Federal Highway Administration.

FTP - Federal Test Procedure.

GVW - gross vehicle weight.

HDD - heavy-duty trucks, diesel.

HDT - heavy-duty trucks.

HDG - heavy-duty trucks, gasoline.

HDV - heavy-duty vehicles.

LDT - total light-duty trucks.

LDV - total light-duty vehicles.

LDVD - light-duty diesel vehicles.

LDVG - light-duty gasoline vehicles.

MARC - Mid-American Regional Council.

Max. - maximum estimate of light- and heavy-diesel vehicle growth trends.

M_g - annual geometric mean pollutant concentration.

MMD - mass median diameter.

N(r,D) - threshold function used in dosage estimation.

NAAQS - National Ambient Air Quality Standard.

NADB - National Air Data Branch.

NASN - National Air Surveillance Network.

NEDS - National Emissions Data System.

ng - nanogram, 10^9 grams.

OXY - oxygenated hydrocarbon fraction of POM.

PNA - polynuclear aromatic hydrocarbon.

PPOM - particulate polycyclic organic matter.

r - slant (or direct) distance between pollutant monitor and roadway, ft.

$S(\bar{D})$ - dosage spectrum.

SET - Sulfate Emission Test.

Sg - standard geometric deviation.

SMSA - Standard Metropolitan Statistical Area.

T - average daily traffic volume.

TRN - transitional hydrocarbon fraction of POM.

TSP - total suspended particulate.

VMT - vehicle miles traveled.

VPOM - vapor phase of polycyclic organic matter.

x - horizontal distance between roadway and pollutant monitor.

z - sampler height.

θ - arctan (z/x).

μg - micrograms, 10^6 gram.

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1.0 SUMMARY

Sales of both light- and heavy-duty diesel-powered vehicles are projected to increase markedly in the next several years. This prediction and new toxicity data have caused attention to be focused on the potential of the resulting increased particulate exhaust emissions from this source having an impact on public health. In evaluating this impact, issues of major concern are the higher particulate emission rates (versus those from comparable gasoline-powered vehicles), the high fraction of the particulate matter in the respirable size range, and the potential toxicity of this particulate matter.

The report presents estimates of the impact diesel-powered emissions will have on the levels of total suspended particulates (TSP) and benzo[a]pyrene (BaP) to which the population is exposed. [Levels of BaP are generally used as an index of total polynuclear aromatic hydrocarbon (PNA) content, primarily because of its potent carcinogenicity.] The values in Table 1-1 show that both TSP and BaP are emitted at a significantly higher rate from the exhausts of diesel-powered vehicles than from comparable, catalytically equipped, gasoline-powered vehicles.

Table 1-1. EXHAUST EMISSIONS OF TSP AND BaP, GASOLINE- VERSUS DIESEL-POWERED VEHICLES

Vehicle category	Emission factors	
	Particulates, g/VMT[a]	BaP, μg/VMT
Light-duty gasoline (catalyst)	0.006-0.015	0.1
(noncatalyst)	0.002-0.25	1.0
Light-duty diesel	0.5	1.0-6.0[b]
Heavy-duty gasoline (catalyst)	0.02-0.05	0.3
(noncatalyst)	0.007-0.90	3.0
Heavy-duty diesel	2.0	4.6-24.6[b]

[a] VMT = vehicle miles traveled.

[b] Low and high emission estimates.

The increasing share of the market projected to be occupied by diesel-powered vehicles will also add these emissions to the population exposure to TSP and BaP. Table 1-2 shows the predicted increase.

Table 1-2. DIESEL SHARE OF NEW SALES BY MODEL YEAR

	Light-duty vehicles, percent		Heavy-duty trucks, percent	
Year	Best estimate[a]	Max.[b]	Best estimate	Max.
1975	0.5	0.5	28.0	28.0
1980	4.0	10.0	31.0	38.0
1985	10.0	25.0	33.0	78.0
1990	10.0	25.0	64.0	99.0

[a] Indicates best diesel market growth estimate.

[b] Indicates maximum diesel market growth estimate.

The characterization and health effects assessment in this report focuses specifically on diesel-generated particulate matter and its components. Particulate emissions from diesel-powered automobiles, largely carbonaceous solids, are about 20 to 50 times higher than those from comparable automobiles burning unleaded gasoline. Diesel particulates are small enough to penetrate deeply into the alveolar region of the respiratory tract. The aerodynamic diameters of a large proportion of diesel exhaust particulates are less than 1 μm. Submicronic particles undergo Brownian motion and are deposited in the lung parenchyma. In some cases (depending on the material), alveolar clearance of particulate matter may not occur for some time. Moreover, experimental evidence suggests that presumably inert carrier substances (e.g. carbon) can affect pulmonary clearance mechanisms and, consequently, retention time. Thus, keeping potentially toxic agents in effective contact with susceptible tissues for prolonged periods increases the likelihood of chemical induction of biological changes and disease in critical organs.

A review of the literature suggests that particulate emissions from diesel engines are not well characterized chemically, physically, or quantitatively; therefore, emission factors include a high degree of uncertainty. Polynuclear aromatic hydrocarbons, one class of organic compounds known to be emitted in diesel exhaust, are likely adsorbed on the carbonaceous particulate. The presence of a number of PNA's other than BaP (of similar structure and having carcinogenic potency) and the lack of reliable quantitative data concerning BaP in diesel engine exhaust nevertheless preclude the unqualified use of BaP as an indicator molecule of total PNA concentration and total carcinogenic potency from this emission source. Emissions of BaP from diesel-powered vehicles and older model gasoline-powered vehicles (not equipped with catalyst) now appear to be about the same. Emissions of BaP from catalyst-equipped vehicles, however, are reportedly lower. Ratios of BaP to total PNA in diesel exhaust and the contribution of BaP content to the total carcinogenic potential of diesel emissions need to be determined if BaP is to be used as an index.

Cancer, particularly of the respiratory tract, is the most significant health problem associated with polycyclic organic matter (POM). This association is based on epidemiological evidence of occupational exposures and information obtained from animal toxicity studies. A correlation between atmospheric concentrations of POM and increased incidence of cancer mortality is suggested, but definitive evidence of a causal relationship is lacking. Other concomitant emission products (e.g. sulfur dioxide, nitrogen oxides, ozone) are suspected of having a potentiating action on the carcinogenic properties of PNA's or possibly resulting in oxygenation of PNA (or POM).

Sulfur compounds are also associated with diesel particulate emissions. The types of sulfate emitted by diesels and the sulfuric acid aerosol portion of the sulfur emission are unknown. Because the health effects of exposure to sulfuric acid differ from those due to exposure to various sulfates, the public health impact of given amounts of diesel sulfur cannot be predicted. Sulfate emissions from diesel-powered cars generally are less than from gasoline-powered cars with catalyst equipment and air injection, but are higher than those from cars not equipped with catalysts or cars with three-way catalyst systems. Sulfate emissions tend to be governed by the sulfur concentration in the fuel.

Assessing health effects of diesel particulate emissions as a function of the toxicity of individual chemical components has obvious limitations. The Ames Salmonella/microsome mutagenicity assay is being used by the EPA as a quick, inexpensive method of establishing priorities for physical and chemical characterization studies and additional toxicologic tests. Several fractions of diesel exhaust particulate show significant mutagenic activity in this bioassay system. Transitional and oxygenated hydrocarbon fractions are the most active. It should be emphasized that these are very preliminary data. Selected fractions of diesel exhaust particulate must be evaluated by other confirmatory bioassays and toxicologic methods to determine the significance of the positive results obtained in these initial screening tests. The positive results obtained in the Ames test indicate the utility of such *in vitro* bioassays to direct the fractionation of diesel particulate. This approach should eventually make it possible to identify the mutagenic components of diesel particulate. Chemical characterization of the active fractions is now in progress.

In addition to *in vitro* bioassays, whole animal studies are being conducted, in which appropriate test species are acutely and chronically exposed directly to dilute diesel exhaust. In this series of experiments, a wide variety of biological parameters are being measured to determine the effects of the emission mixture on the respiratory system. Results obtained from inhalation studies using animals, the Ames mutagenicity assays, and other confirmatory *in vitro* bioassay systems will help define potential health hazards and estimate the degree of toxicity associated with exposure to diesel emissions and components thereof.

Diesel exhaust particulate fractions have been found to be potentially mutagenic and certain POM is known to be carcinogenic, and diesel particulates are projected to increase significantly the population TSP exposure, particularly in areas near roadways. Total ambient BaP levels appear to be somewhat less affected by diesel-generated BaP, but they also were higher near roadways. It is concluded, therefore, that diesel vehicle exhaust particulates do represent a health hazard.

The impact of diesel-generated particulates on population exposure to TSP and BaP is projected for 1981, 1983, 1985, and 1990. A detailed particulate emission inventory is developed for a representative test city (Kansas City, Missouri) for a reference year (1974). Emissions from all sources except diesel are assumed to remain constant. The impact of diesel-generated particulates on the population at 165 grid points in this city is determined on the basis of best estimate and maximum diesel growth cases for each projection year. A total emissions inventory for Kansas City in 1974 shows that highway vehicle exhaust emissions accounted for 1.6 percent of total particulate loading (1,006 of 64,033 tons/year). Table 1-3 shows projected motor vehicle exhaust emission rates to be consistently lower than those in 1974, but diesel vehicles represent a progressively larger fraction of the total. Trends in BaP emissions are similar; however, insufficient data are avail-

Table 1-3. PROJECTED MOTOR VEHICLE PARTICULATE EXHAUST EMISSIONS FOR KANSAS CITY

(in tons/yr)

Vehicle category	1974	1981		1983		1985		1990	
		Best est.	Max.	Best est.	Max.	Best est.	Max.	Best est.	Max.
Gasoline-powered									
- Light-duty	733	200	197	119	94	76	70	61	53
- Heavy-duty	102	111	301	111	94	111	76	90	36
Diesel-powered									
- Light-duty	8	29	67	65	163	106	258	190	429
- Heavy-duty	163	190	205	206	239	209	291	295	415
Total	1006	530	573	501	589	502	695	636	933

* Increasing diesel-powered vehicle introduction corresponds to decreasing gasoline-powered vehicle use.

able to make a total BaP emission inventory of Kansas City.

Table 1-4 presents an evaluation of predicted peak levels of diesel-generated TSP, based on an analysis of Kansas City data.

Table 1-4. PREDICTED PEAK LEVELS OF DIESEL-GENERATED TSP FOR KANSAS CITY

	Maximum diesel contribution, percent				
	1974	1981		1990	
TSP, μg/m^3		Best est.	Max.	Best est.	Max.
Regional annual geometric mean	0.35	0.45	0.56	0.96	1.73
Regional 24-hr maximum	1.05	1.34	1.66	2.86	5.16
Roadside[a] annual geometric mean	3.85	4.95	6.16	10.56	19.03
Roadside 24-hr maximum	11.48	14.76	18.36	31.48	56.73

[a] Typical residential dwelling located adjacent to a major thoroughfare.

The maximum regional impact of diesel-generated TSP is projected for 1990. It constitutes 2.3 percent of the primary national ambient air quality standard (NAAQS) for the annual mean and 3.4 percent of the secondary NAAQS for the maximum 24-hour period. Estimated maximum roadside impact from diesel-generated TSP in 1990 is 25.3 (annual NAAQS of 75 μg/m^3) and 37.8 percent (24-hour standard of 150 μg/m^3) of the respective NAAQS. Thus, diesel-generated particulate emissions represent a potentially significant population exposure impact.

Peak diesel BaP concentrations of 0.02 and 0.13 ng/m^3 for low and high BaP emission estimates, predicted in a similar manner, are used for the roadside annual geometric mean. Corresponding values for the 24-hour maximum roadside impact are 0.12 and 0.69 ng/m^3. The corresponding upper range of population exposures to BaP from coke oven operations averages 20 to 100 ng/m^3 annually. Thus, it appears that the BaP impact from diesel-powered vehicles is relatively low.

The distribution of population exposure to TSP, developed for each projection case, includes an estimation of exposure extremes for each grid area. These data are extrapolated to generate national population exposures, based on the mean of all ambient monitoring station annual average TSP levels for Kansas City compared with those from other selected Standard Metropolitan Statistical Areas (SMSA's). The SMSA population and urban SMSA population density are also considered in this analysis. The maximum diesel impact case is the 1990 maximum diesel growth case, which projects that 1 million people will be exposed to diesel exhaust TSP at a level greater than 2.4 $\mu g/m^3$ annual geometric average. Table 1-5 summarizes these data for the population exposed to greater than the primary NAAQS of 75 $\mu g/m^3$.

Table 1-5. ESTIMATED POPULATION EXPOSURE TO MORE THAN THE FEDERAL STANDARD FOR TSP

Projection year	Millions of people exposed to more than 75 $\mu g/m^3$			
	Best estimate		Maximum growth	
	Total exposed	Diesel contribution	Total exposed	Diesel contribution
1981	62.7	0.4	62.8	0.4
1983	64.3	0.4	64.7	0.8
1985	66.4	0.4	67.3	1.5
1990	71.1	1.0	72.3	2.2

Diesel contribution to overall TSP exposure levels is relatively greater in areas of high TSP concentration. In locations with TSP levels of more than 120 $\mu g/m^3$, diesel vehicle emissions increased the number of people exposed by 3.8 to 10.1 percent; whereas in lower exposure areas, the diesel impact is frequently less than 2 percent of the total. Thus, diesel TSP emissions tend to have the greatest impact in locations where emissions exceed National Ambient Air Quality Standards. These high diesel exposure locations generally correspond to maximum roadside diesel TSP impact locations described above.

A methodology similar to that used to estimate TSP is used to estimate national BaP exposure attributable to diesel vehicles. Total BaP exposure relationships are based on urban ambient monitoring data. Diesel exhaust appears to have a lower impact on total BaP exposure than on TSP exposure. The maximum diesel BaP impact occurs in the 1990 high emission estimate case that has the maximum diesel growth projection, which results in a diesel contribution of less than 1 percent of the total concentration for the 5 percent of the population receiving the highest exposure. Because ambient BaP measurements are quite sparse, these data really amount to crude estimates.

2.0 INTRODUCTION

The Clean Air Act amendments require the setting of particulate emission standards for various classes and categories of vehicles, beginning with 1981 models. In support of proposed standards for particulate emissions from light- and heavy-duty diesel vehicles, this report presents a preliminary assessment of the impact of diesels on projected air quality and the potential public health effects associated with total suspended particulate (TSP) and particulate polycyclic organic matter (PPOM) in diesel exhaust.

Because of the very short time allowed to complete this assessment, some abbreviated procedures were used. A single compound, benzo[a]pyrene (BaP), is used as an indicator of PPOM because it is the only polycyclic organic substance for which ambient air quality and diesel emissions data are currently available. Although normally an indicator of polycyclic aromatic hydrocarbons (PNA's) in urban environments, BaP is used here as an indicator of the broader class of polycylic organics, PPOM.

An assessment of the effects of diesel exhaust particulate on human health is presented first to aid in interpreting the potential health impact significance of projected increases in exposure of the population to diesel-derived particulates and to provide a basis for the model used to estimate public risk from exposure. Also presented are available data on the chemical constituents of diesel particulate, together with an overview of the health effects literature regarding significant particulate fractions and the status of the toxicity assessment of diesel particulates.

In assessing potential exposures of the general population to dosages of TSP and BaP attributable to diesel exhaust, projections are developed for 4 years: 1981, 1983, 1985, 1990. Consideration is given to the introduction of diesel-powered vehicles into the total automotive market in each of these years, in terms of a best estimate and a maximum growth value for light-duty and heavy-duty vehicles (percent of sales in each class).

To help estimate the potential impact of increasing diesel vehicle sales on ambient particulate air quality, an analysis is made of the distribution of population exposures to TSP and BaP. The analysis indicates both the total exposures to TSP and BaP and the exposures due to diesel vehicle exhaust only.

Based on these exposure estimates, a further estimate is made of the impact of particulate exhaust emissions from diesels on exposure of the population to TSP. For each projection case the dose-distribution for TSP and for the diesel-derived portion of TSP is determined with respect to a representative city (Kansas City, Missouri, in this analysis). Both TSP and the diesel contributions to TSP are determined at 165 grid locations in the city by use of the Air Quality Dispersion Model (AQDM). Based on census tract population data, population versus dose-level relationships are developed. Then, based on national trends in TSP exposure in a representative sampling of all standardized Metropolitan Statistical Areas (SMSA's), distributions are developed for exposure of the total national population to TSP and to the diesel-derived portion.

The impact of BaP from diesel-powered vehicles is estimated from a relatively sparse data base in a similar, though less involved, manner. The dose-distribution of BaP from diesels is developed for each projection year. National exposure relationships are developed, based on projections of growth in diesel vehicle sales, national population distributions, and relationships of national trends to those predicted for Kansas City. The total national distribution of exposures to BaP is determined by summing the exposures attributable to coke-oven emissions and the exposures attributable to all other sources. These calculations are based on ambient air quality data from urban stations of the National Air Surveillance Network (NASN). The BaP impact attributable to diesels is determined for each projection year, for each diesel-vehicle growth case, and also for two diesel-vehicle emission rates (a total of 16 cases).

3.0 CHARACTERIZATION AND HEALTH EFFECTS ASSESSMENT OF DIESEL PARTICULATE EMISSIONS

The discussion that follows summarizes available technical information on the composition and associated health effects of diesel particulate emissions. It intentionally excludes regulated gaseous components of diesel exhaust (i.e. carbon monoxide, nitrous oxides, hydrocarbons), some of which may have synergistic or potentiating biological effects with particulate organic matter. It is difficult to assess any associated risk to human health from diesel exhaust because data on health effects are limited, particle size is variable, and particulate composition varies both qualitatively and quantitatively. This section therefore first characterizes particulate emissions from diesel-powered vehicles by their chemical composition (i.e. their major and trace elements, PNA's, sulfates, etc.), then presents an overview of the literature on animal and human health effects of the major chemical groups identified. It gives particular attention to the carcinogenicity and mutagenicity of identified compounds or fractions isolated from diesel exhausts.

3.1 PARTICULATES

3.1.1 Emissions

The term "particulate" encompasses a class of emission products, variable in composition, that exist in the atmosphere in the form of finely dispersed solids or aerosols. Total particulate emissions from diesel-powered automobiles are much higher than those from gasoline-powered automobiles. Gasoline engines burning leaded fuel emit particulates that are mainly the product of the combustion of lead and lead scavengers (ethylene dibromide and ethylene dichloride). Catalyst-equipped gasoline engines that burn unleaded fuel produce a sulfuric acid mist over the catalyst, which, in addition to the associated water of hydration, forms the particulate emissions from such vehicles. Table 3-1 compares the results of several particulate emission tests on typical diesel-powered automobiles with the results of tests on gasoline-powered automobiles. The mass of particulates emitted during the Federal Test Procedure (FTP) increases with size of the diesel engine, and all the measurements are much higher than the levels obtained on gasoline-powered cars, particularly on the two vehicles using unleaded gasoline.

Table 3-1. PARTICULATE EMISSIONS FROM DIESEL VERSUS GASOLINE PASSENGER CARS[1]

Vehicle type	Engine displacement,[2] CID	Total particulates (FTP), g/mile
Diesel vehicles:		
VW Rabbit[3]	90	0.291
Peugeot 504[4]	129	0.397
Mercedes 240D[5]	146	0.477
Mercedes 300D[5]	183	0.490
Oldsmobile 350[3a]	350	0.917
Gasoline vehicles:		
VW Rabbit[3] - unleaded gasoline	90	0.007
Oldsmobile 350[3] - unleaded gasoline	350	0.011
Typical leaded gasoline car[5]	b	0.240

[a] Early prototype model.

[b] Data not available.

The characterization of diesel exhaust particulates has only recently begun to receive the degree of attention already given to emissions from gasoline-powered vehicles. Information on their physical and chemical characteristics is therefore limited. Data on the elemental composition, trace metal content, and organic soluble fractions of diesel exhaust particulate are given in Table 3-2. Particulates emitted by diesel engines are composed primarily of carbon and hydrogen, with relatively small amounts of nitrogen, sulfur, and oxygen. Their carbon content appears to be independent of fuel composition. Although trace metals are present in diesel particulate emissions (those of potential health concern are mercury, lead, vanadium, and strontium), the quantities involved limit their danger to health. Significant calcium and barium particulate emissions result from the use of smoke suppressant additives containing these two metallic elements.

3.1.2 Pulmonary Deposition

Diesel particulates are small enough to penetrate deeply into the alveolar region of the respiratory tract. Mentser and Sharkey[13] investigated the composition of diesel particulates as a function of particle size. They used seven fraction sizes ranging from <0.2 to $\geq$3.0 μm in diameter. The calculated effective aerodynamic diameters of the particulate fractions are shown in Table 3-3. Weight measurements of particulates in the seven stages indicated that more than 50 percent of the total mass of particulates in any given experiment were collected on the backup filter (stage 7). Particle size distributions from a light-duty diesel engine were also measured by Laresgoiti *et al.*[14]

Table 3-2. ELEMENTAL AND TRACE METAL COMPOSITION OF DIESEL EXHAUST PARTICULATES[7]

Reference	Engine	Fuel	Average weight % by elements					
			Carbon	Hydrogen	Nitrogen	Sulfur	Oxygen	Σ
6	D.D.A.D 6V-71	EM-238-F	80.6	10.7	3.2	1.01		95.5
		EM-239-F	83.9	10.9	1.4	0.79		97.0
		EM-240-F	79.6	12.2	a	0.32		92.1
		EM-241-F	86.6	10.5	a	0.90		98.0
		EM-242-F	84.9	9.8	1.5	0.83		97.0
	Caterpillar 3208	EM-238-F	87.2	1.9	0.5	1.90		91.5
		EM-239-F	84.5	2.2	0.4	1.47		88.6
		EM-240-F	85.2	2.1	0.1	0.46		87.9
		EM-241-F	74.9	2.9	0.9	1.66		80.4
		EM-242-F	79.7	1.6	0.8	1.67		83.8
8	Detroit Diesel 6L-771T	1-D						
			b 69.7	10.2	0.1	0.6		80.6
			c 85	13	0.1	0.1	0.2	98.4
		2-D	b 68.2	10.2	0.4	2.3		81.1
			c 82	12	0.2	0.8	4.5	99.5
		1 1/2-D	b 74.2	10.8	0.2	1.0		86.2
			c 80	12	0.4	0.1	a	92.5
	Cummins NTC-290	1-D	b 78.2	4.7	1.7	2.8		87.4
			c 70	11	3.6	a	a	84.6
		2-D	b 60.9	3.3	0.2	4.3		68.7
			c 84	12	0.6	a	a	96.6
		1 1/2-D	b 80.5	8.1	0.9	3.3		92.8
			c 78	11	0	a	a	89.0

[a] None detected or trace.

[b] Percent of element in total particulates.

[c] Percent of element in organic soluble fraction of particulates.

(continued)

Table 3-2 (continued)

Reference	Engine	Fuel
	Cummins NTC-290	**2-D and 1 1/2-D plus 0.25% (vol) smoke suppressant additive** Ca: 3.6 - 12 g/hr Ba: 1.7 - 2.1 g/hr
	Detroit Diesel 6L-71T	Trace metal analysis in μg/cm^2 of collection filter **A. Fuels without additives:** Ca: 0 - 3.10 μg/cm^2 Cu: 0 - 0.12 μg/cm^2 Zn: 0.15 - 4.02 μg/cm^2 Pb: 0 - 0.48 μg/cm^2 Sr: 0 - 0.48 μg/cm^2 Ba: 0 **B. Fuels with smoke suppressant additives:** Ca: 1.66 (idle) - 52.57 μg/cm^2 Cu: 0 μg/cm^2 Zn: 0.07 - 1.44 μg/cm^2 Pb: 0 - 0.34 μg/cm^2 Sr: 0 - 0.15 μg/cm^2 Ba: trace (idle) - 7.66 μg/cm^2 V : 0 - 0.42 μg/cm^2
	Cummins NTC-290	**A. Fuels without additives:** Ca: 0 - 1.61 μg/cm^2 Mn: 0 - trace μg/cm^2 Cu: 0 - 0.10 μg/cm^2 Zn: 0 - 1.89 μg/cm^2 Pb: 0 - 0.72 μg/cm^2 Sr: 0 - 0.10 μg/cm^2 Ba: 0 μg/cm^2 **B. Fuels with smoke suppressant additives:** Ca: 3.86 - 58.58 μg/cm^2 Mn: 0 - 0.28 μg/cm^2 Cu: 0.11 - 0.18 μg/cm^2 Zn: (idle)- 0.52 μg/cm^2 Pb: - - 0.42 μg/cm^2 Sr: 0.05 - 0.13 μg/cm^2 Ba: 1.35 - 8.94 μg/cm^2

(continued)

Table 3-2 (continued)

Reference	Engine	Fuel	
	Detroit Diesel 6L-71T	**2-D and 1 1/2-D plus 0.25% smoke suppressant additive**	
			Ca: 7.7 - 14 g/hr **1.1 - 3.4 g/hr**
9	**Detroit Diesel 6V-71**	**5 Fuels**	**Trace elements in particulates** **Pb: 5.3 - 6.6 μg/filter** **Mn: 4.0 - 4.0 μg/filter** **Hg: 3.4 (one fuel) μg/filter** **P : 0.6 - 1.6 μg/filter** **S : 2.5 - 14 μg/filter** **Na: 0.29 (one fuel) μg/filter** **Zn: 1.0 - 1.3 μg/filter** **Cu: 1.5 - 11 μg/filter** **Ca: 1.2 - 2.8 μg/filter** **V : 0.44 - 0.73 μg/filter**
10	**Nissan LDMV**	**1 Fuel**	**Weight % of element in exhaust particulates** **C : 70.42 - 72.84** **H : 0.43 - 2.22** **N : 5.51 - 8.81** **Fe: 0.13 - 0.15** **Cu: 0 - 0.02** **Zn: 0.07 - 0.16** **S : 0.51 - 1.12**
	Opel LDMV	**1 Fuel**	**Weight % of element in exhaust particulates** **C : 72.4 - 77.9** **H : 4.7 - 6.1** **N : 0.9 - 3.5** **Fe: 0.13 - 1.08** **Cu: 0 - 0.01** **Zn: 0.16 - 0.29** **P : 0 - 0.09** **S : 0.49 - 1.05**
	Nissan LDVM	**3 Fuels**	**Weight % of element in exhaust particulates** **C : 69.2 - 76.6** **H : 1.4 - 2.0**

(continued)

Table 3-2 (continued).

Reference	**Engine**	**Fuel**	
11	**Single Cylinder**	1 Fuel	**Weight % of element in ashed particulates** Si: 0.5 - 0.75 Fe: 0.1 - 0.35 Ca: 0.02 - 0.5 Ba: 0.02 - 0.5 Cr: 0.001 Cu: 0.0005- 0.001 Ti: 0.001
12	Diesel trucks (highway)	Unknown	Ba emission rates from trucks estimated to be 0.001 to 0.0015 g/mile. Assumes Ba emitted from diesel fuel and crankcase oil.

Their results, summarized in Figure 3-1, indicate that about 90 percent of the particles were smaller than 1 μm and 99 percent were smaller than 2 μm. Data from a study conducted by the Bureau of Mines (Table 3-4) suggest that the mass median diameter (MMD) of diesel exhaust particulates is approximately 0.3 μm, and that (in two engines tested) fuel, operating cycle, and engine type had little effect on exhaust particulate size.[15]

Table 3-3. AERODYNAMIC DIAMETERS OF DIESEL EXHAUST PARTICULATES COLLECTED IN VARIOUS STAGES OF AN ANDERSON SAMPLER[13a]

Sample no.	Filter stage	Aerodynamic diameter, μm[b]
81,[c] 91[d]	1	≥3.0
82, 92	2	2.0
83, 93	3	1.3
84, 94	4	0.8
85, 95	5	0.4
86, 96	6	0.2
87, 97	7 (backup)	<0.2

[a] Data supplied by A. J. Strazisar of PMSRC.

[b] Effective aerodynamic diameter calculated for the following sampling conditions: gas flow, 3.0 ft^3/min; gas temperature, 100°F; impaction efficiency, 50 percent.

[c] Engine mode for samples 81-87: 2200 rpm, full load.

[d] Engine mode for samples 91-97: 600 rpm, no load.

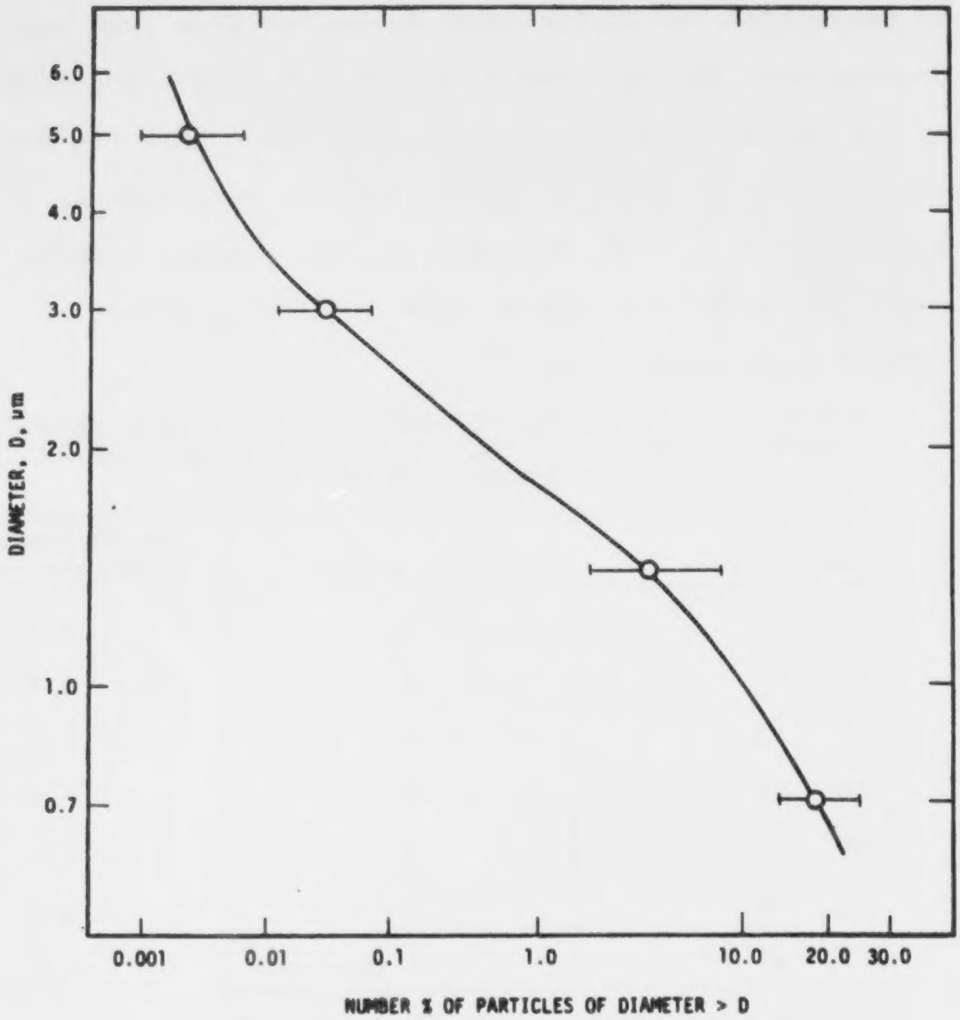


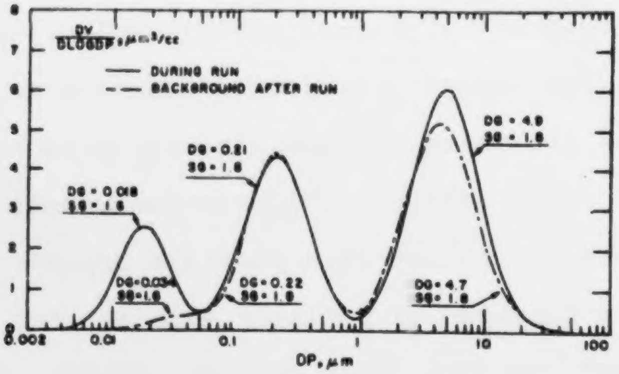
Figure 3-1. Particle size distribution.[14]

Circles: average of 24 data points for speeds ranging from 800 to 3100 rpm and for loads ranging from 0 to 75% of full load. Bars: data scatter.

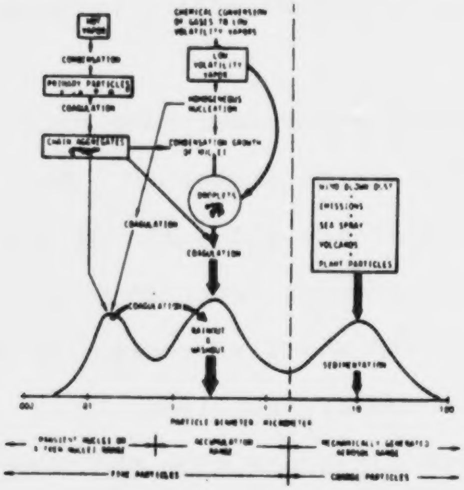
Table 3-4. DIESEL EXHAUST PARTICLE SIZE[7]

Reference	Engine type	Operating mode	Fuel	Particulate size, µm MMD
15	Caterpillar 6-cyl. four-cycle 1D1	Idle	2-D	0.25
			Heavy 2-D	0.28
			1-D	0.32
		Intermediate speed @ no load	2-D	0.27
			Heavy 2-D	0.36
			1-D	0.24
		Rated speed @ half load	2-D	0.35
			Heavy 2-D	0.40
			1-D	0.30
		Rated speed @ full load	2-D	0.29
			Heavy 2-D	0.40
			1-D	0.47
		Intermediate speed @ full load	2-D	0.25
			Heavy 2-D	0.24
			1-D	0.19
			30 Test average = 30	
	Cummins 6-cyl four-cycle D1	Idle	2-D	0.44
			Heavy 2-D	0.32
			1-D	0.47
		Intermediate speed @ no load	2-D	0.39
			Heavy 2-D	0.35
			1-D	0.43
		Rated speed @ half load	2-D	0.20
			Heavy 2-D	0.29
			1-D	0.22
		Rated speed @ full load	2-D	0.20
			Heavy 2-D	0.23
			1-D	0.27
		Intermediate speed @ no load	2-D	0.29
			Heavy 2-D	0.35

Particulates indiscriminately adhere to solid surfaces and to each other. Among the properties of particles that influence the strength of the adhesive bond are chemical composition, the presence or absence of moisture or oily films, electrical charge, and physical characteristics.[16] The force of the adhesion of one particle to another cannot be reliably predicted now, but simple test methods are available to determine this. It is generally assumed that airborne particles that contact each other continue to adhere, i.e., the "collision efficiency" is 100 percent.[16] If it is assumed that diesel exhaust particulates behave similarly, the size distribution of these particulates could vary depending on the site and time of measurement. Available evidence indicates that most diesel particulates at the tailpipe fall within a relatively small size range. This distribution, however, may not accurately characterize the size of the diesel exhaust particulates in the ambient environment. The adherence of diesel particulates to one another and their interaction with other atmospheric particles may result in the formation of larger particles. Coalescence of solid particles results in flocculent, isometrically shaped, or threadlike aggregates. These particle dynamics are illustrated in Figure 3-2.[17] Although these data depict the impact of gasoline vehicle emissions, the



Trimodel model particle distribution measured during and after vehicle proving grounds tests. Note that during the test the accumulation and coarse particle modes (center and right modes) have not changed significantly from the background conditions. On the other hand, practically all of the volume of the nuclei mode (left mode) is contributed by the cars on the roadway.


HOT VAPOR
CONDENSATION
PRIMARY PARTICLES
COAGULATION
CHAIN AGGREGATES
CHEMICAL CONVERSION OF GASES TO LOW VOLATILITY VAPORS
LOW VOLATILITY VAPOR
HOMOGENEOUS NUCLEATION
CONDENSATION GROWTH OF NUCLEI
DROPLETS
COAGULATION
COAGULATION
COAGULATION
RAINOUT & WASHOUT
WIND BLOWN DUST + EMISSIONS + SEA SPRAY + VOLCANOS + PLANT PARTICLES
SEDIMENTATION
.01
.1
1
2
10
100
PARTICLE DIAMETER, MICROMETER
ACCUMULATION RANGE
MECHANICALLY GENERATED AEROSOL RANGE
FINE PARTICLES
COARSE PARTICLES

Schematic of a trimodal atmospheric aerosol size distribution showing the principal modes, main sources of mass for each mode, and the principal processes involved in inserting mass and removing mass from each mode.

Figure 3-2. Impact of vehicle exhaust on ambient particulate size distribution data for gasoline-powered vehicles.[17]

particle dynamics of diesel vehicle emissions should be similar. The impact of particle dynamics on pulmonary deposition and retention and ultimately on health, cannot be predicted until reliable quantitative models are developed.

Figure 3-3 illustrates particle deposition probabilities as a function of particle size as they relate to respiratory regions. This size-deposition relationship depicts average particle deposition probabilities for a man breathing spontaneously under sedentary conditions. Although deposition probabilities for the submicronic range are theoretical, particle size-deposition relationships can be used in risk evaluations of particulate exposure because they provide useful models for intake or dose estimations and are helpful in understanding pulmonary clearance processes.

As previously mentioned, many diesel exhaust particulates have diameters of less than 1 μm. Submicronic particles easily penetrate all parts of the respiratory system. They continually undergo Brownian motion deposition, which predominates in the alveolar region, although some of them remain airborne and are expelled.

Particulate clearance from the lung parenchyma (alveoli) seems to involve an absorptive mechanism whereby the particle or its dissolved phase moves into the blood or

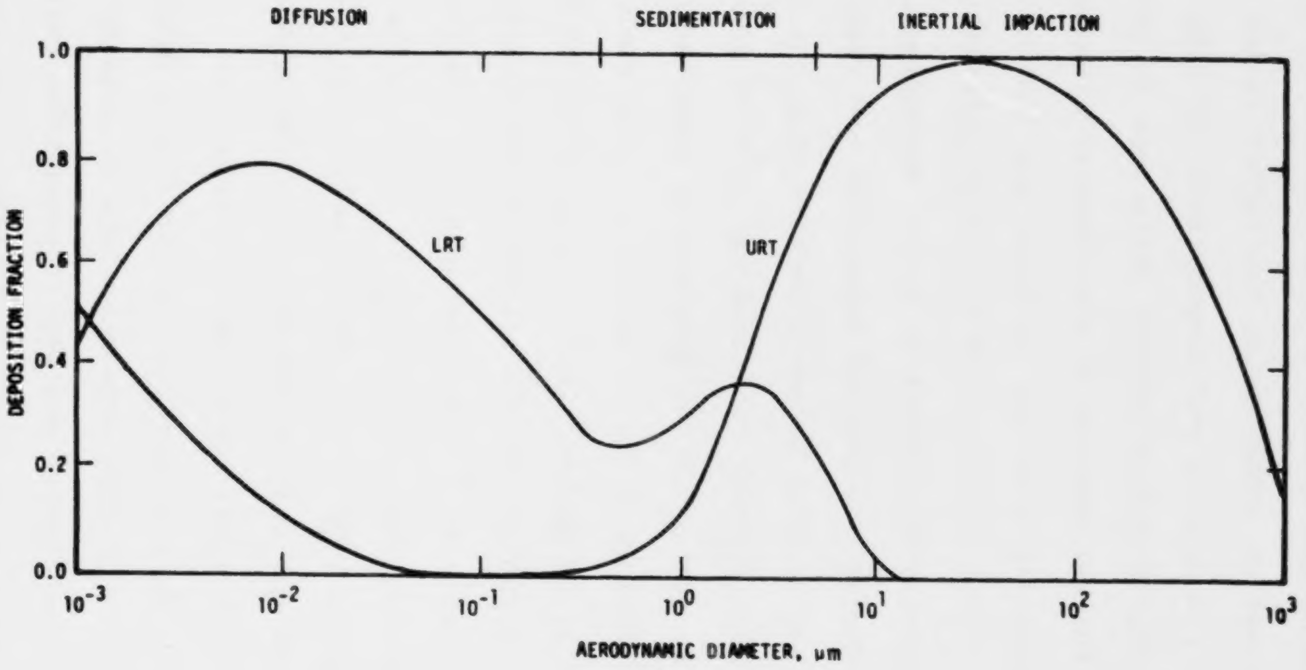


Figure 3-3. Particle size deposition probabilities.[18]

lymph. This mechanism appears to depend on permeability considerations and on endocytosis; the latter is the process, including pinocytosis and phagocytosis, whereby foreign materials are engulfed by migratory cells such as pulmonary macrophages. Further details of the alveolar clearance mechanism, especially quantitative data, are lacking. It is known, however, that clearance of insoluble particles from the alveoli may vary from hours to years, depending on the particulate material. Increased deposition and retention in these susceptible tissues become important when one realizes that even an inert carrier substance can contain potentially toxic materials, either in the particle or adsorbed on it. Such materials include PNA's or sulfates. Once such compounds are deposited in the alveoli, they cannot be resuspended easily and may not be cleared or metabolized for a long time, if at all.[19] This increases the likelihood of chemically inducing disease at critical sites in the body. The health implications of particulate emissions thus appear to depend not only on particle size and deposition, but also on the chemical nature of the particles.

Many of the data on particulates in diesel emissions are limited to qualitative determinations of organic components, or to descriptive analytical procedures that tend to emphasize technique and instrumentation rather than composition. Review of the literature, however, suggests that diesel engine particulates are not well characterized, either chemically or physically, and emission factors are uncertain.

3.2 POLYCYCLIC ORGANIC MATTER

Polycyclic organic matter (POM) is defined as organic matter that contains two or more ring structures which may or may not be substituted by other chemical groups.[33] Any combustion process involving fossil fuels or compounds containing carbon and hydrogen can form POM. The amount formed in a given combustion process depends on the efficiency of the process. Polycyclic organic matter can be further separated into the particulate phase (PPOM) or vaporous phase (VPOM). One group of aromatic compounds of PPOM, the PNA's, is particularly important because it includes several carcinogenic materials.

Polynuclear aromatic hydrocarbons have been detected in fractions of PPOM obtained from diesel exhaust.[1,2,4,7,13] They are believed to result from 1) incomplete combustion of materials in the fuels, 2) synthesis of aromatic hydrocarbons of lower molecular weight, and/or 3) pyrolysis of lubricating oil. The first of these sources is believed to be the most important.[20] Table 3-5 lists PNA's isolated from diesel exhaust particulates that demonstrate some

Table 3-5. FREQUENCY OF OCCURRENCE OF FORMULAS FOR CARCINOGENIC COMPOUNDS IN DIESEL EXHAUST PARTICULATES[13]

Formula	Carcinogenic compound with corresponding formula	Carcinogenicity[a]	Molecular weight	Frequency of occurrence, 30 samples
$C_{18}H_{12}$	Chrysene	±	228.0936	28
	Benzo[c]phenanthrene	+++		
	Benz[a]anthracene	+		
$C_{20}H_{12}$	Benzo[a]pyrene	+++	252.0936	16
	Benzo[b]fluoranthene	++		
	Benzo[j]fluoranthene	++		
$C_{20}H_{14}$	Benz[j]aceanthrylene	++	254.1092	2
$C_{20}H_{16}$	7,12-Dimethylbenz[a]anthracene	++++	256.1248	1
$C_{21}H_{14}$	Dibenzo[a,g]fluorene	+	266.1092	2
$C_{20}H_{13}N$	Dibenzo[c,g]carbazole	+++	267.1045	1
$C_{22}H_{12}$	Indeno[1,2,3-cd]pyrene	+	276.0936	3
$C_{22}H_{14}$	Dibenz[a,h]anthracene	+++	278.1092	2
	Dibenz[a,j]anthracene	+		
	Dibenz[a,c]anthracene	+		

[a] Carcinogenicities are given in Ref. 25, according to the following code:

± uncertain or weakly carcinogenic
+ carcinogenic
++, +++, ++++, strongly carcinogenic.

degree of carcinogenic activity. Most of these compounds have molecular weights from 228 to 302 and frequently exist in several isometric forms. The frequency with which they appeared in samples of diesel exhaust particulates is given in the last column of the table. PNA formulas $C_{18}H_{12}$ and $C_{20}H_{12}$ were by far the most prevalent. The first, corresponding to chrysene or its isomers, occurred in 28 of 30 exhaust particulates. The second formula, benzo[a]pyrene or its isomers, occurred in 16 of 30 samples.

Table 3-6, compiled by Lyons,[21] lists PNA compounds detected in samples of various atmospheric pollutants. The author noted that several compounds possess the anthracene stem as part of their structural configuration. Polycyclic hydrocarbons occurring in highest concentration in the three soot extracts appeared to have two to five condensed rings.

Primarily because of its potent carcinogenicity and frequency of occurrence, BaP has typically been measured and used in vehicular emission research and air pollution monitoring as an indicator of total PNA concentration. Consequently, the bulk of available data is in terms of BaP. As the above examples have indicated, other polycyclic organic materials of similar structure and carcinogenicity occur in vehicular exhaust emissions, but reliable quantitative data for BaP and other PNA's from diesel engine

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Table 3-6. COMPOUNDS DETECTED IN VARIOUS ATMOSPHERIC POLLUTANTS (G), (D), AND (A)[a] SAMPLES[21]

Compound	G	D	A
Naphthalene	+	-	-
Acenaphthylene	+	+	+
Anthracene	+	+	+
Phenanthrene	-	+	-
Anthracene derivatives	+	+	+
Pyrene	+	+	+
Fluoranthene	+	+	+
Alkylpyrene	+	-	-
Benz[a]anthracene	+	+	+
Chrysene	+	-	+
Benzo[e]pyrene	+	+	+
Perylene	+	+	+
Benzo[a]pyrene	+	+	+
Benzo[ghi]perylene	+	+	+
Benzo[b]fluoranthene	+	+	+
Anthanthrene	+	+	+
Tetracene	+	-	-
Coronene	+	+	+
Dibenz[a,h]anthracene	+	-	-
4-Dibenzo[a,l]pyrene	+	+	-
Benzo[k]fluoranthene	+	+	+
Pentaphene	+	+	-
Dibenzo[a,l]naphthacene	+	-	-
Dibenzo[a,h]pyrene	+	-	-
Dibenzo[a,e]pyrene	+	-	-
Dibenzo[b,pqr]perylene	+	-	-
(Dibenzofluorene?)	-	+	+
Tribenzo[h,rst]pentaphene	+	-	-
Indeno-1,2,3-fluoranthene?	-	+	-

[a] G: gasoline soot sample
D: diesel soot sample
A: general atmospheric soot sample.

+: detected in sample
-: not detected in sample

Methodology: fluorescence and UV and visible absorption analysis of particulate extracts following chromatographic fractionation.

exhaust are lacking. Although BaP could be used as an indicator molecule of urban pollution, its use as an accurate index of total PNA emissions from a single source such as diesel exhaust is questionable. Nonetheless, total PNA's in vehicular exhaust emissions continue to be estimated and are often expressed solely on the basis of BaP.

Polyaromatic hydrocarbon emissions are thought to be related to fuel and lubricating oil composition and combustion efficiency. Analysis of diesel fuels for PNA compounds has shown that diesel fuels tend to contain lower concentrations (up to 422 ppb of BaP) of PNA compounds than gasoline (up to 3000 ppb of BaP).[21] Although one might expect higher concentrations of PNA's in the less volatile diesel fuel, gasolines actually contain much higher concentrations of catalytically processed aromatic hydrocarbons.[1]

Table 3-7 shows results of tests for BaP emissions from a single diesel car[4] compared with results from three gasoline cars without catalysts.[23,24] Emission levels of BaP from both combustion sources are about the same (i.e. 1.57 and 1.95 μg/mile). Use of oxidative catalysts and other pollution control devices has reportedly reduced all PNA emissions from gasoline-fueled engines by about 99 percent, which would place a catalyst-equipped car well below a diesel as a source of PNA's.[20] These results should be interpreted with caution because the sampling and analytical procedures used by the different investigators were not uniform.

Table 3-7. BENZO[A]PYRENE EMISSIONS FROM DIESEL VERSUS GASOLINE CARS[1]

Vehicle type	BaP emissions (FTP), μg/mile
Peugeot 504 diesel[4]	1.57
Average of three 1969-72 noncatalyst gasoline cars[23,24]	1.95

Note: Data on catalyst-equipped gasoline cars were not available for the same test procedure, but investigators using a different test procedure[20] have observed about 99 percent elimination of all PNA emissions with catalysts.

It has been clearly established that carcinogenic PNA's are emitted in the form of particulate matter from gasoline and heavy-duty, diesel-powered engines.[23,25] It is uncertain whether polycyclic organic matter condenses out as discrete particles after cooling, or condenses on surfaces of existing particles after formation during combustion. Light-duty diesel PNA characterization is even less well defined and is currently part of an important investigation by the U.S. Environmental Protection Agency.[26] It is thought that PNA emissions may be chemically combined, i.e. adsorbed, with particulate matter simultaneously emitted from light-duty diesel engines. The significance of this from the standpoint of health effects has not yet been fully elucidated, but it seems likely that carcinogenic PNA compounds adsorbed on fine particulates could be inhaled and brought into effective contact with susceptible cells of the lining of the tracheobronchial tree and parenchyma.

Some of the factors affecting pulmonary deposition have already been discussed. In certain experimental animals, presumably inert carrier substances have been shown to have an important effect on the concentration time determinants of toxic inhalants. Experiments by Boren[28] have shown that carbon functioning as an absorbent greatly increases the damaging action of nitrogen dioxide on the lung. When tritiated BaP is incorporated in carbon or asbestos, clearance from the lungs of hamsters is slowed.[29] An increase in the carcinogenic effect of BaP by means of carbon and carrier particles[30,26] and hematite[32] has also been demonstrated. These experimental results are interesting in view of the observation that particulate material emitted by diesel engines is largely carbonaceous and contains carcinogenic PNA's as well as other potentially toxic compounds. Although some experimental evidence suggests carrier substances can affect pulmonary clearance mechanisms, their exact role can only be surmised.[27]

There is clear evidence that occupational exposure to airborne particulate organic matter, particularly the polynuclear aromatic fraction, is responsible for specific adverse biological effects in man.[27] These effects include cancer of the lungs and skin, nonallergic contact dermatitis, photosensitization reactions, hyperpigmentation of the skin, folliculitis, and acne. In concentrations found in the atmosphere, PPOM does not appear to cause any of these cutaneous effects; similarly, there is no clear evidence that, by themselves, such materials as airborne BaP directly influence the pathogenesis of nonneoplastic lung diseases (e.g. bronchitis and emphysema).[27]

Many screening methods have been used to evaluate the carcinogenicity of PPOM. They have utilized pure samples of organic compounds of the types found in the ambient environment, total PPOM and fractions collected from urban atmospheres, as well as organic fractions isolated from combustion sources. The carcinogenic potential of pure PNA's and extracts of airborne materials has been tested on various whole animals, tissue cultures, organ cultures, and microorganisms. Methods employed on whole animals included skin painting, subcutaneous injection, systemic inoculation, oral intake, local implantation (in lung, bladder, or other organs), intratracheal inoculation, and inhalation. Animal and bioassay data relating to the toxicity of PPOM are briefly reviewed in a scientific and technical assessment report published by the U.S. Environmental Protection Agency.[33]

Both animal experiments and epidemiologic data indicate that pulmonary cancer of environmental origin involves a complex series of factors and events in which PNA's constitute only one of the carcinogenic factors. The possibility of synergistic or cocarcinogenic effects of other environmental agents must also be considered. Irritant or toxic gases (e.g. SO_2, NO_x, and ozone), existing in various concentrations in the atmosphere, are known to have a potentiating action on the carcinogenic properties of PNA's.[34,35] This has been demonstrated by the higher incidence in CAF/Jax mice of pulmonary adenomas produced by simultaneous exposure to ozone and carcinogens.[36] Work by Laskin et al.[37] suggests additive or potentiating effects of SO_2 in BaP carcinogenicity in rats. Individual susceptibility to the carcinogenic action of PNA's can also be influenced by smoking habits, occupational exposures, age, and coexistent viral or other pulmonary diseases.

Examination of epidemiologic studies suggests that there is an "urban factor" in the pathogenesis of lung cancer in man. Although a major factor in the causation of human pulmonary cancer is cigarette smoking, it alone does not account for the increased incidence of this disease. It appears that the incidence of lung cancer among urban dwellers is twice that of those living in rural areas; within urban communities, the incidence is even greater where fossil-fuel emission products are highly concentrated in the air.[27] A strong link between cancer mortality and nearness to traffic has been reported in a study by Blumer et al.[38] This epidemiological study, which is based on a population study of a Swiss mountain town from 1958 through 1970, found death from cancer nine times more frequent among those who lived near the local highway than those who lived 440 yards or more away. The level of PNA's was very high in soil near the highway (300 mg/kg) and less abundant farther away (4 to 8 mg/kg). The composition of the PNA's in soil samples resembled that of PNA's in automobile exhaust. Low values in town and close to industry but remote from the highway and high PNA values outside of town but near the highway suggest a correlation between automobile traffic and PNA content of soils. These results also indirectly suggest a correlation between automobile traffic and the observed mortality from cancer in this area. Although mortality data on lung cancer are not specific and etiologic factors and PNA emission sources were not conclusively determined, the public health implications and the need for efforts to control engine exhaust are considerable.

Polycyclic hydrocarbons have not been shown to be teratogenic, although a number of other chemical carcinogens exhibit this biologic action. The teratogenicity of community atmospheric pollutants and defined components thereof has not yet been tested in mammalian species by inhalation or by parenteral administration.

No mutagenic effects from PPOM or its PNA components have been found in animals in vivo, but studies in this area have not been extensive.[33] One might postulate that urban susceptibility to carcinogens may have been induced by mutagenic mechanisms over several generations; however, pure samples of a few selected PNA's of the types found in diesel exhaust and organic fractions of collected diesel particulates have demonstrated mutagenic activity in in vitro bioassay systems. Improved and simplified techniques, such as the Ames mutagenesis bioassay, are expected to yield significant information on genetic variations and, ultimately, on cellular mechanisms of cancer. Preliminary results obtained from experiments in which seven diesel exhaust fractions were tested in the Ames system are described in Section 3.5.

3.3 SULFATES

The contribution of diesel-powered passenger cars to the emission of sulfates, or sulfuric acid, is of interest in view of the considerable attention given to this subject since the advent of catalyst-equipped automobiles. Table 3-8 shows values of sulfate emissions for the same group of diesel-powered automobiles discussed in the section on particulates.[1] Sulfate emissions were measured using the same type of dilution tunnel and filtration system developed for particulate measurements, but with a different driving cycle. This was developed especially to represent the conditions under which sulfate emissions cause the highest local exposures to people. Comparison with the average values for gasoline cars with and without catalysts shows that the diesels fell between the low extreme represented by the noncatalyst and three-way catalyst cars, and the high extreme represented by the catalyst cars with air injection. The values for diesels tended to increase in proportion to vehicle size, which is reasonable because this is the order of increasing fuel consumption. Each diesel car apparently converted about the same fraction of the total sulfur in the fuel to sulfates (about 2 percent). The fuel used in the diesel car test work was a typical No. 2 diesel fuel containing 0.228 percent sulfur by weight.

Typical diesel fuel reportedly contains about eight times the amount of sulfur of typical gasoline.[2] Because sulfate emissions tend to be proportional to fuel sulfur level, a reduction in the sulfur level of diesel fuel would reduce sulfate emissions.

Table 3-8. SULFATE EMISSIONS FROM DIESEL VERSUS GASOLINE PASSENGER CARS

Vehicle type	Sulfate (SET), g/mile
Diesel vehicles:	
VW Rabbit[3]	0.007
Peugeot 504[4]	0.007
Mercedes 240D[4]	0.014
Mercedes 300D[5]	0.016
Oldsmobile 350[3]	0.017
Gasoline vehicles:	
Average noncatalyst car[39]	about 0.001
Average catalyst car with air injection[37]	about 0.030
Average catalyst car without air injection[39]	about 0.008
Three-way catalyst car[39]	about 0.001

Although the sulfur emitted by gasoline-powered cars is essentially all sulfuric acid, it is not known what types of sulfate are emitted by diesels nor how much of it is sulfuric acid. Because the health effects of exposure to sulfuric acid differ from those of exposure to other sulfur compounds, the impact of given amounts of diesel sulfates in terms of health effects cannot yet be predicted.

There is no basis as yet for predicting whether increased use of diesel-powered cars would cause a net increase or decrease in sulfate emissions, because it is not known whether future gasoline-powered cars will use predominantly three-way catalysts (low sulfate emissions), or oxidizing catalysts with air injection (high sulfate emissions).

3.4 MINOR COMPONENTS

Aldehydes and other oxygenates of low molecular weight, as well as aliphatic, phenolic, and light aromatic hydrocarbons, are minor volatile components of diesel exhaust that are most probably emitted in the vapor phase. Since this assessment is restricted to diesel exhaust particulate and its major components, potential health effects associated with specific vapor constituents are not discussed. It should be noted, however, that potentiating or cocarcinogenic effects have been attributed to some of these compounds. Thus, the toxic potential of PPOM in diesel exhaust could be influenced by other emission factors. The possibility of adsorption and absorption of gaseous and condensed substances on diesel particulates requires further study.

3.5 CURRENT RESEARCH STATUS

Identification and quantitative analysis of potentially toxic components of diesel exhaust particulate, and subsequent testing of these compounds in their pure form under laboratory conditions, is a common method of estimating the toxicological impact of an emission source. Chemical characterization and toxicological testing of all potentially toxic compounds in diesel particulates, however, would be an immense, time-consuming, and probably futile task. Because of this, faster, less expensive screening procedures are currently used to establish priorities for physical and chemical characterization studies and additional toxicologic tests. The Ames Salmonella/microsome assay has gained wide use as a quick, economical, and reliable screening method to determine if a chemical agent or mixture is mutagenic or likely to cause cancer. In whole animal studies, the Ames assay procedure has been shown to be 85 to 90 percent accurate in detecting substances that are carcinogenic; and it has about the same accuracy in identifying substances that are not carcinogenic in animals.

In a joint ESRL/HERL (RTP) project, seven diesel exhaust fractions obtained from both a two-stroke and a four-stroke diesel engine were tested for mutagenicity with the Ames test (by V. Simmon, Stanford Research Institute).[40] Preliminary data indicate that several fractions of diesel exhaust particulate are mutagenic. These findings are not altogether unexpected, because previously reported studies had identified chemicals in engine exhaust products that are known to be mutagenic or carcinogenic.

The fractions were examined with five tester strains of Salmonella typhimurium (TA 1535, TA 1537, TA 1538, TA 98, and TA 100) with and without the standard liver microsomal metabolic activation system. The experiments were conducted in a dose response fashion (6 to 8 doses/fraction per tester strain), and each experiment was repeated (except in 3 of the 14 samples, where the sample size was limiting).

The most mutagenic fraction was the transitional hydrocarbon (TRN) fraction, which produced a 20-fold increase over spontaneous mutation rates in TA 1538 at approximately 40 µg/plate. (The transitional hydrocarbon fraction was described as that portion of the neutral fraction composed of the middle polar species.)* The oxygenated hydrocarbon (OXY) fraction produced a 20-fold increase over spontaneous mutation rates at 100 µg/plate. These results are from the four-stroke engine samples. Similar data and other experimental details are available for the two-stroke engine samples. The order of mutagenic activity for the most active fractions was the same for both engines: TRN>OXY>ACD (acidic).

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* Telephone conversation with Frank Black, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina on December 8, 1977.

These fractions were mutagenic without metabolic activation, indicating the predominance of direct-acting mutagens (e.g. the 7, 8-diol-9, 10-epoxide of benzo[a]pyrene) that do not require enzymatic conversion as provided by microsomal metabolic activation. In several fractions, the microsomal metabolic activation increased the mutagenic activity above that observed in the absence of microsomal activation, indicating the presence of lesser amounts of compounds that require metabolic activation (e.g., benzo[a]-pyrene).

Mutagenic activity was primarily observed with tester strains that respond to frameshift mutagens (e.g. ICR-191, benzo[a]pyrene, aflatoxin B_1, and 7,12-dimethylbenz[a]-anthracene).

These results indicate the utility of such *in vitro* bioassays to direct the fractionation of diesel particulate. If the resources and personnel were available to pursue this approach, it should be possible to identify the mutagenic components of diesel particulates. Compounds recently identified in the TRN fraction, the fuel, or whole exhaust are now the subject of a literature search pertaining to microbial mutagenesis. In addition to further fractionation and bioassay, additional development work is required to bioassay either the crude particulate itself or a simple extract. This would allow evaluation of the relative mutagenic activity of a variety of engines, fuels, pollution control devices, etc.

Several selected fractions of the diesel exhaust particulate will be evaluated by other confirmatory bioassays, such as the mammalian cell mutagenesis and neoplastic transformation methods. Experiments are also in progress to evaluate the relative toxicity of these fractions in several _in vitro_ systems. If suitable _in vitro_ procedures can be developed, comparative studies of various diesel and gasoline engines will be consucted.

Because the biological impact of isolated chemical components of a mixture is different from that of the mixture as a whole, inhalation studies are being conducted in which animals are exposed directly to whole diesel exhaust. In this series of experiments, a wide variety of biological parameters are being measured to determine the effects of the exhaust on the respiratory systems of several mammalian species. Acute, subacute, and chronic inhalation exposures are being conducted using appropriate dilutions of diesel exhaust emissions. Metabolic effects of the emissions are examined in terms of their specific biochemical reactions with lung tissue, alveolar macrophages, and subcellular organelles. Early biochemical changes that precede the appearance of overt symptoms of toxicity or a disease state may eventually prove to be clinically significant. In addition, an inherent part of this approach is the consideration of any additive, synergistic, potentiating, and/or cocarcinogenic effects from exposure to mixtures of diesel exhaust components and particulates. Results obtained from inhalation studies using animals and from in vitro bioassays will provide an estimate of the degree of toxicity associated with diesel exhaust and components thereof and help define potential health hazards.

A substantial amount of research is now either under way or being planned to obtain more information on diesel exhaust particulate emissions from both light- and heavy-duty diesel-powered vehicles. This work includes a) the collection of particulates and isolation of organic soluble components of particulates from a variety of diesel-powered vehicles under various driving schedules and fuel combinations; b) determination of the biological activity of the total particulates, the total organic extract of the particulates, and the individual fractions of the extract in various biological test systems; c) chemical characterization of those particulate fractions that show activity in various biological test systems; d) calculation of emission rates of these exhaust products for various vehicles, driving schedules, and fuel combinations; and e) prediction of likely concentrations of these biologically active fractions on and near the roadway and in the ambient environment. In the next 6 to 9 months, appropriate agencies should have further data from which to draw additional conclusions.

Scientific evidence, both direct and indirect, indicates that diesel exhaust particulate emissions pose a toxic hazard to humans. Chemical analysis of diesel exhaust particulates reveals the presence of a number of scientifically recognized carcinogens. Diesel exhaust particulates, on which carcinogenic PNA's may be adsorbed, are well within the respirable size range. Several diesel exhaust fractions have demonstrated mutagenic activity in *in vitro* bioassay systems. The studies and short-term tests performed thus far have helped characterize the diesel particulate and have identified chemical components or fractions thereof with toxic, carcinogenic, or mutagenic activity. However, these studies alone do not provide sufficient data to make a definitive estimate of the public health risk, if any, that may be associated with emissions from diesel-powered vehicles. Chronic whole animal exposure studies and/or human epidemiological data are generally required to perform such health risk assessments. The data that are just emerging from ongoing and planned research efforts will permit this extremely important risk assessment to be performed and provide a basis for establishing scientific and rational environmental quality standards for diesel exhaust emissions.

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4.0 TEST CITY METHODOLOGY AND PROJECTIONS

This chapter discusses the methodology used to project the air quality impact of increased diesel-powered motor vehicle usage in a test city. The impact is first assessed in terms of ambient air concentrations of TSP and BaP through the use of appropriate and available diffusion modeling tools, and then in terms of the number of persons exposed to varying levels of TSP and BaP concentrations. The assessment covers a base year (1974) and four projection years (1981, 1983, 1985, and 1990).

The following paragraphs discuss the rationale used in selecting a test city and a diffusion modeling approach.

Selecting the Test City

Ideally, selection of a test city for a study of this type would be based on numerous criteria such as total population, population density, age of the city, diversity of industrialization, number of motor vehicles and roadway miles per capita, and other relevant variables. All of these would help to identify an average or typical large (i.e., greater than 200,000 population) metropolitan area. The selected city would then be modeled, and the resulting predicted-versus-measured air pollution concentrations would be extrapolated to the national data levels of large urban areas.

Because the time constraints imposed upon the study precluded any possibility of using such a process, the criterion for selection becomes simply: "What seemingly typical large urban area has a usable diffusion model that is current and quickly accessible to the consultant?"

The Kansas City metropolitan area meets this criterion quite well. First, it is generally representative of most large urban areas in the United States. It is situated on the border of Missouri and Kansas and encompasses 8 counties and 111 cities. The portion of the area on which this study focuses covers 255 square miles and has a population of approximately 760,000, which indicates an average density of about 2990 people per square mile.[1] Figure 4-1 shows a map of the Kansas City area, highlighting the portion addressed in this study.

Second, Kansas City could also provide a recent set of usable diffusion modeling data. Data used as input in a 1976 modeling effort were readily accessible to the consultant and in a format that could be quickly applied to the work on this report.

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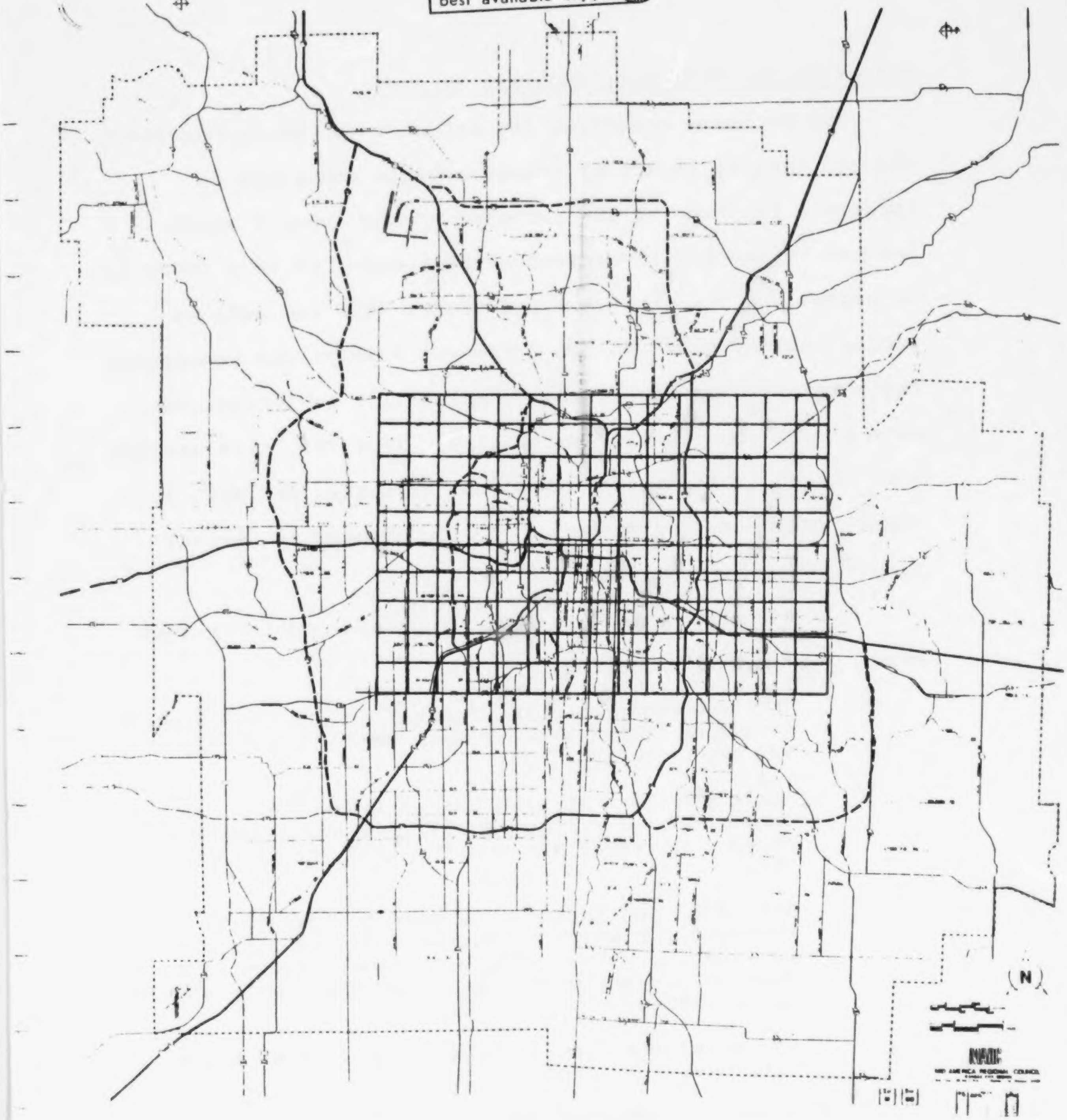
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Figure 4-1. The test city study area - Kansas City, Missouri.

Selecting the Diffusion Modeling Approach

The decision regarding the approach to use in modeling the air quality impact of diesel vehicle emissions is largely a function of the purposes of the overall study. Reduced to its key ingredients, the purpose of this study is to assess the impact of two pollutants (TSP and BaP) on public health, based on two different assumptions concerning the rate at which new diesel vehicles will be introduced into the on-road vehicle population. (For TSP, this assessment refers to the impact on annual exposure; for BaP, it simply refers to the number of people exposed to various ranges of concentrations.)

Criteria used to select an appropriate model for this study include the following:

- The model(s) must yield annual and 24-hour concentrations. Even shorter time period predictions may be useful for BaP.
- The model(s) must have been validated in a general sense and, in a more specific sense, calibrated against measured air quality data for the test city.
- Available population data must be comparable to the area for which diffusion model results are obtainable. Thus, if a micro-scale model is to be used, micro-scale population exposure data should be available.
- The model must accept traffic data as an input variable.

Four separate diffusion models were readily recognized as candidates for consideration: the Air Quality Display

Model (AQDM), the Climatological Display Model (CDM), APRAC-IA, and HIWAY. The first two are regional scale TSP and SO_2 models that predict annual concentrations at many different receptors. The last two are carbon monoxide (CO) models that predict hourly concentrations at many different receptors. The APRAC-IA model yields regional "background" and street canyon peak concentrations. The HIWAY model yields peak concentrations for open terrain, corridors, or intersections. Each CO model can be run so as to produce 8 to 24 hours worth of predicted values, but the cost of preparation and computation time is high.

Based on the criteria, none of the available models was entirely suitable for the task at hand. The HIWAY model will not predict annual concentrations, it has not been validated for use in modeling particulate emissions, and it does not generate data that are compatible with regionally based population data. The first two objections also apply to the APRAC 1A model. The HIWAY model might possibly be used to generate maximum predicted 1-hour TSP and BaP concentrations in the vicinity of a typical roadway; however, it would probably take longer than allowed for the project if done in conjunction with regional, longer term modeling.

The CDM was objected to for three different reasons: 1) it requires meteorological data that are not available in many areas (including Kansas City); 2) it can predict short-term concentrations only with the aid of statistical assumptions, which are not necessarily valid; and 3) it is not designed to predict the regional impact of motor vehicle emissions alone.

Although the meteorological data required by AQDM are normally available in most cities (including Kansas City), the other two objections to the CDM apply to the AQDM as well. In addition, the AQDM is known to have a tendency to overpredict the impact of area sources (of which motor vehicles are a subset).

After consideration was given to the drawbacks of all the available options,[2] the AQDM was judged to be the best for this task. The capabilities and usage of this model are discussed fully in the referenced document, Air Quality Display Model.[3]

4.1 NONMOTOR VEHICLE EMISSIONS

Base Year Emissions

Because no BaP emissions data are available from point and nonvehicular area sources in the Kansas City area, no effort is made to predict overall concentrations of that pollutant. Rather, efforts are directed toward defining the impact of BaP emissions from diesel vehicles.

Particulate emissions data covering point and area sources (summarized in Table 4-1) are from a recent report

Table 4-1. PARTICULATE EMISSIONS IN TEST CITY (1974)

Source category	Annual emissions, ton/yr	Percent of total
Point sources		
Power plants	37,253	57.8
Mineral products	2,563	4.0
Grain mills and elevators	4,113	6.4
Refineries	1,186	1.8
Chemical process	135	0.2
Metals	1,639	2.5
Automotive	92	0.1
Fiberglass	2,871	4.5
Miscellaneous	296	0.5
Subtotal	50,148	77.8
Stationary area sources		
Natural gas combustion	418	0.6
LPG combustion	48	0.1
Distillate oil combustion	63	0.1
Residual oil combustion	106	0.2
Coal combustion	0	0.0
Wood combustion	1	0.0
Incinerators	10	1.0
Subtotal	646	1.0
Mobile sources		
Highway vehicles (diesel exhaust)	171	0.3
Highway vehicles (gasoline exhaust)	835	1.3
Highway vehicles (tire wear)	676	1.0
Railroad	167	0.3
Aircraft	4	0.0
River vessels	n.d.	0.0
Subtotal	1,853	2.9
Fugitive dust sources		
Paved streets	10,377	16.1
Unpaved streets, parking lots	110	0.2
Cleared areas, storage areas	50	0.1
Construction, aggregate storage	420	0.7
Railroad yards	204	0.3
Agriculture	225	0.3
Subtotal	11,789	18.3
Total	64,436	

entitled, Analysis of Probable Particulate Nonattainment in the Kansas City AQCR.[4] These data, which are used to predict base year concentrations, have been modified in the following ways. First, emissions from one of the power plants have been increased substantially to reflect findings concerning the effect of equipment malfunctions, shutdowns, and inefficiencies;* second, paved road emissions (reentrained dust) have been reduced by approximately one-third to reflect the findings of a recent study;[5] and third, emissions from motor vehicles are separated into tire-wear emissions and exhaust emissions. The latter category has been further split into emissions from diesel-powered and gasoline-powered vehicles. Total emissions from motor vehicles also differ slightly from those in the reference material as a result of the use of recently revised emission factors.

These modified data are used to compare annual concentrations predicted by AQDM with measured values, and the resulting relationship is used to adjust predicted values. As shown in Table 4-2, these predicted values agree fairly well with the measured TSP data from 18 monitoring sites: an average predicted arithmetic mean of 73.1 $\mu g/m^3$, compared

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* Communication with Mr. P. Stablein, Kansas City Health Department, Air Quality Division. November 1977.

Table 4-2. COMPARISON OF MEASURED VERSUS PREDICTED TSP CONCENTRATIONS, KANSAS CITY (1974)

Receptor No.	Receptor name	Predicted arithmetic mean, $\mu g/m^3$	Measured arithmetic mean, $\mu g/m^3$	Deviation of predicted from measured values, $\mu g/m^3$
177	No. Brighton	69	75	6
178	Waterworks	84	65	19
179	No. Kansas City	86	74	12
180	KC Health Department	72	89	17
181	Morse School	69	116	47
182	NASN site	81	90	9
183	Leeds	68	94	16
184	6600 Independence	78	87	9
185	Fairfax	83	76	7
186	Deramus	83	86	3
187	Municipal Airport	83	108	25
188	Independence Courthouse	62	93	31
189	Claycomo	66	89	23
190	ASB Bridge	84	118	34
191	No. Liberty	62	78	16
192	UMKC Campus	62	69	7
193	Klamm Park	67	86	19
194	Turner H.S.	57	69	12
Average		73.1	86.8	17.3

Ratio of measured to predicted values = 86.8/73.1 = 1.187

with an average measured concentration of 86.8 μg/m^3. The mean deviation of the predicted from the measured concentrations is 17.3 μg/m^3. It is considered neither useful nor appropriate to use a regression equation to correct predicted values, however, because none of the predicted or measured values is below 55 μg/m^3. Because all data pairs tend to cluster at the upper end of the concentration range, predicted values are corrected by a ratio of average measured to predicted concentrations, i.e., 1.187. A factor of 0.933, obtained from Reference 4, is used to convert arithmetic mean predictions to geometric means. This value is based on a statistical analysis of arithmetic and geometric means observed at the 18 Kansas City TSP monitoring sites.

Projection Year Emissions

Numerous uncertainties are associated with projecting future emissions. Perhaps the most basic relate to the location and magnitude of new sources, how rapidly point-source compliance schedules are met, and how extensively nontraditional fugitive dust sources are controlled. Because of these uncertainties, it is assumed that all emission sources other than diesel vehicles will remain constant in the test city through 1990, both as to location and emission rate. This assumption probably causes future emissions to be overestimated, but, concurrently, it focuses attention on the impact of diesel vehicles alone (should all other factors remain constant).

4.2 MOTOR VEHICLE EXHAUST EMISSIONS

This section explains the derivation of 1974 motor vehicle exhaust information presented in Table 4-1 and provides additional information necessary to project emissions in 1981, 1983, 1985, and 1990. The focus is on estimating overall vehicle miles traveled (VMT) by grid within the study area, allocating those VMT to six vehicle categories, developing weighted particulate and BaP emission factors, and using these data to calculate emissions for the base year and each of the projection years.

Estimating Vehicle Miles Traveled

Vehicle miles traveled are estimated for six different vehicle-engine classes: gasoline-powered and diesel-powered light-duty vehicles (LDVG and LDVD); gasoline-powered and diesel-powered light-duty trucks (LDTG and LDTD); gasoline-powered heavy-duty trucks (HDG); and diesel-powered heavy-duty trucks (HDD). National percentage of VMT by vehicle type, vehicle type distribution by age, and assumed rate of diesel-powered vehicle introduction are used in conjunction with Kansas City traffic distribution and growth rate data.

Base Year VMT - According to data provided by the Mid-American Regional Council (MARC), the agency responsible for transportation planning in the Kansas City area, 1974 VMT totalled 2851.5 x 10^6 in the study area during the course of the work reported in reference 4. Traffic volume was plotted by link segment on a map of the area and assigned to the 2 km by 2 km grid network shown in Figure 4-1.

Projection Year VMT - Local data were used to project VMT to 1990. A growth of 36 percent is predicted for the Kansas City metropolitan area from 1970 to 1990.[6] Assuming this growth occurs linearly, the following rates are calculated from 1974 figures.

Projection year	Fraction of 1974
1981	1.117
1983	1.151
1985	1.186
1990	1.270

No data are readily available on which to base growth projections by geographical area; therefore, it is assumed that growth will occur uniformly throughout the urban area. This assumption probably results in an overestimation of both VMT and emissions in the central city core and an underestimation of VMT in the suburban ring.

Distributing VMT Among Vehicle-engine Classes

Once VMT totals have been generated for the base and projection years, the next step is to distribute these totals among the six vehicle categories described above. The distribution varies with the year for which calculations are made because of the impact of increasing use of diesel vehicles. The following paragraphs describe the techniques used to distribute VMT for the base year and each of the four projection years.

Base Year Distribution - Figure 4-2 summarizes the procedure used to distribute VMT among the six vehicle-engine classes. In essence, the base-year national urban VMT distribution is calculated, and it is assumed that the resulting distribution applies uniformly throughout the Kansas City study area. The fractions arrived at are then applied to the grid VMT generated previously.

The following base-year national VMT data were obtained from the Federal Highway Administration (FHWA).[7]

Vehicle type	National VMT x 10^6
All personal passenger vehicles	1,013,068
Commerical buses	2,610
School and other non-revenue buses	2,450
Single-unit trucks	211,460
Combination trucks	56,059
All motor vehicles	1,285,647

Data necessary to calculate urban VMT for light-duty vehicles are assumed to be equivalent to those reported for personal passenger vehicles. In the case of light- and heavy-duty trucks, however, some data manipulating is required.

The U.S. Environmental Protection Agency (EPA) recently calculated that light-duty trucks contribute 60 percent of total truck VMT.[*] This percentage is applied to the truck VMT data reported above.

To calculate HDG and HDD shares of single-unit and combination truck VMT, commercial and school bus VMT must be assigned to each of these two classes. Again, the methodology used by the EPA[*] is applied. A synthesis of the calculation procedures used yields the following equations:

HDG VMT = (single-unit trucks - LDT) 0.91 + school bus VMT + (combination trucks) 0.16 Eq. (1)

HDD VMT = (single-unit trucks - LDT) 0.09 + commercial bus VMT + (combination trucks) 0.84 Eq. (2)

These national VMT totals must then be converted to national urban VMT values, which is accomplished by applying urban factors developed by EPA:[*]

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[*] Memorandum from M. E. Williams, U.S. EPA, re Urban/Rural Vehicle Miles Travelled Split by Mobile Source Category, dated December 4, 1975.

Category	Urban fraction
LDV	0.57
LDT	0.47
HDG	0.43
HDD	0.33

Urban VMT are then converted to fractions of total VMT by dividing them by the total urban VMT. The following fractions result:

Category	Urban VMT x 10^6	Fraction of total urban VMT (1974)
LDV	577,449	0.830
LDT	75,440	0.108
HDG	24,847	0.036
HDD	17,914	0.026

In the absence of better data, it is assumed that diesel-powered vehicles comprise 0.5 percent of the LDV and LDT VMT in 1974.

At this point, these fractions are applied to the grid VMT developed previously to produce a VMT total for each vehicle-engine class in each study area grid.

Projection Year Distribution - Figure 4-2 summarizes the procedure used to distribute VMT among the six vehicle-engine classes for each projection year. This procedure is complicated by the need to calculate fractions of assumed VMT by model year for each of the six vehicle-engine classes (reasons discussed under Assigning Emission Factors later in this chapter). In the discussion of the procedure that follows, emphasis is given to the method of generating fractions

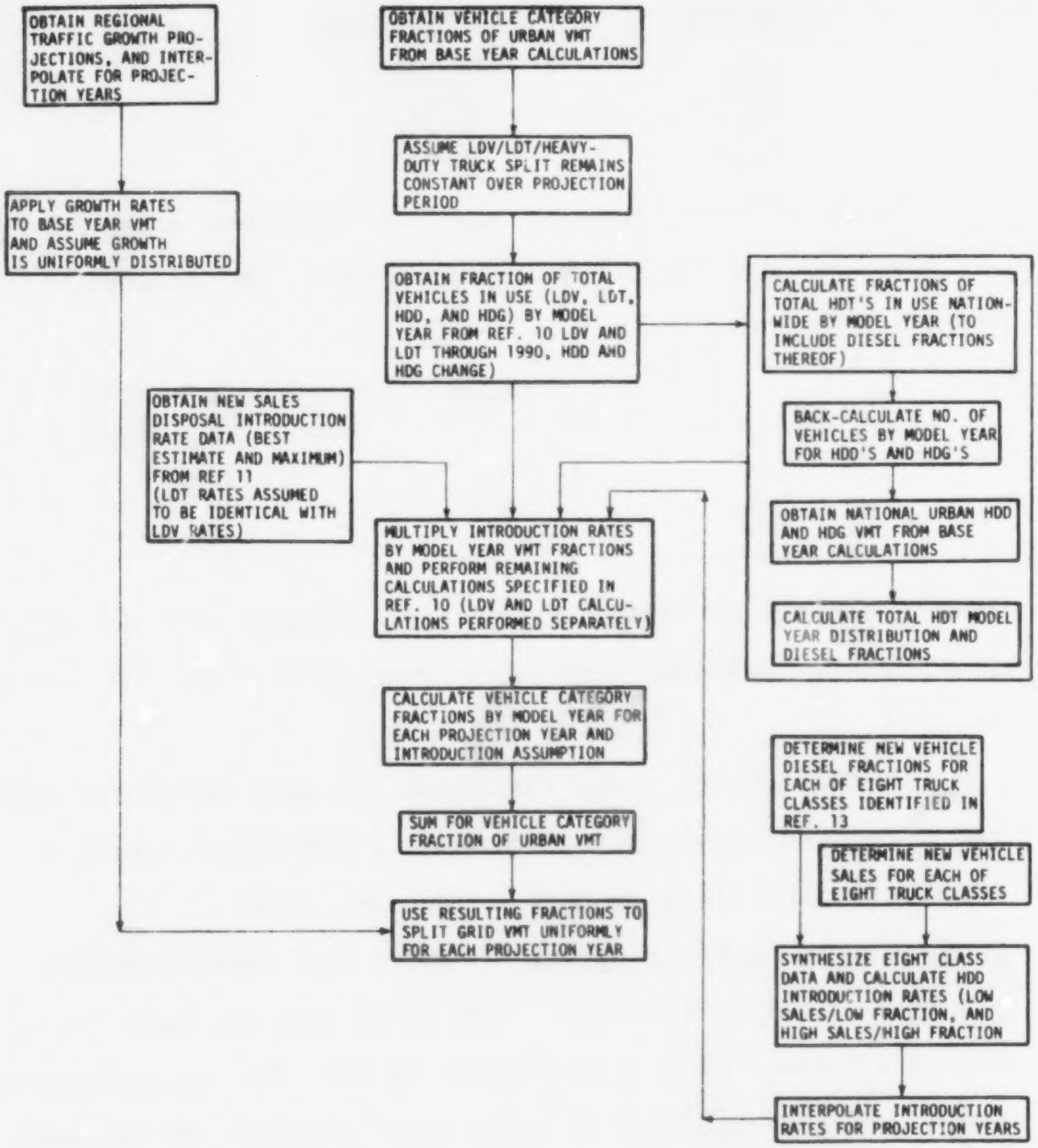
OBTAIN REGIONAL TRAFFIC GROWTH PROJECTIONS, AND INTERPOLATE FOR PROJECTION YEARS
APPLY GROWTH RATES TO BASE YEAR VMT AND ASSUME GROWTH IS UNIFORMLY DISTRIBUTED
OBTAIN VEHICLE CATEGORY FRACTIONS OF URBAN VMT FROM BASE YEAR CALCULATIONS
ASSUME LDV/LDT/HEAVY-DUTY TRUCK SPLIT REMAINS CONSTANT OVER PROJECTION PERIOD
OBTAIN FRACTION OF TOTAL VEHICLES IN USE (LDV, LDT, HDD, AND HDG) BY MODEL YEAR FROM REF. 10 LDV AND LDT THROUGH 1990, HDD AND HDG CHANGE)
CALCULATE FRACTIONS OF TOTAL HDT'S IN USE NATIONWIDE BY MODEL YEAR (TO INCLUDE DIESEL FRACTIONS THEREOF)
BACK-CALCULATE NO. OF VEHICLES BY MODEL YEAR FOR HDD'S AND HDG'S
OBTAIN NATIONAL URBAN HDD AND HDG VMT FROM BASE YEAR CALCULATIONS
CALCULATE TOTAL HDT MODEL YEAR DISTRIBUTION AND DIESEL FRACTIONS
OBTAIN NEW SALES DISPOSAL INTRODUCTION RATE DATA (BEST ESTIMATE AND MAXIMUM) FROM REF 11 (LDT RATES ASSUMED TO BE IDENTICAL WITH LDV RATES)
MULTIPLY INTRODUCTION RATES BY MODEL YEAR VMT FRACTIONS AND PERFORM REMAINING CALCULATIONS SPECIFIED IN REF. 10 (LDV AND LDT CALCULATIONS PERFORMED SEPARATELY)
CALCULATE VEHICLE CATEGORY FRACTIONS BY MODEL YEAR FOR EACH PROJECTION YEAR AND INTRODUCTION ASSUMPTION
SUM FOR VEHICLE CATEGORY FRACTION OF URBAN VMT
USE RESULTING FRACTIONS TO SPLIT GRID VMT UNIFORMLY FOR EACH PROJECTION YEAR
DETERMINE NEW VEHICLE DIESEL FRACTIONS FOR EACH OF EIGHT TRUCK CLASSES IDENTIFIED IN REF. 13
DETERMINE NEW VEHICLE SALES FOR EACH OF EIGHT TRUCK CLASSES
SYNTHESIZE EIGHT CLASS DATA AND CALCULATE HDD INTRODUCTION RATES (LOW SALES/LOW FRACTION, AND HIGH SALES/HIGH FRACTION
INTERPOLATE INTRODUCTION RATES FOR PROJECTION YEARS

Figure 4-2. Procedures for calculating projection years' grid VMT by vehicle category for two diesel introduction rate assumptions.

of annual VMT by model year for HDD's and diesel introduction rates for each vehicle class.

The first step is to obtain vehicle-engine class fractions of urban VMT from the base-year calculations discussed above. Diesel- and gasoline-powered fractions for each vehicle class are combined to obtain the following urban fractions:

Vehicle class	Fraction of Urban VMT (1974)
LDV	0.830
LDT	0.108
HDT	0.062

It is assumed that these fractions will remain constant through 1990.

Next, data concerning the fractions of total LDV, LDT, HDG, and HDD vehicles used nationwide (by model year) are obtained from the EPA.[8] Again it is assumed that these fractions, with the exception of those for HDD and HDG, will remain constant through 1990. Table 4-3 presents the base-year fractions used in the study.

The third step is to convert these vehicle-in-use factors to VMT factors by model year for each of the six vehicle-engine classes. To do that, however, it is necessary to account for the projected influx of diesel vehicles. This is a rather straightforward process for light-duty vehicles and trucks, but is somewhat more complex for heavy-duty trucks. Two stages are required: first, the calcula-

Table 4-3. BASE-YEAR FRACTIONS OF TOTAL VEHICLES IN USE NATIONWIDE

Age, years	Fraction of total vehicles in use nationwide			
	LDV	LDT	HDD	HDG
1	0.081	0.061	0.077	0.037
2	0.110	0.095	0.135	0.070
3	0.107	0.094	0.134	0.078
4	0.106	0.103	0.13[illegible]	0.086
5	0.102	0.083	0.099	0.075
6	0.096	0.076	0.090	0.075
7	0.088	0.076	0.082	0.075
8	0.077	0.063	0.062	0.068
9	0.064	0.054	0.045	0.059
10	0.049	0.043	0.033	0.053
11	0.033	0.036	0.025	0.044
12	0.023	0.024	0.015	0.032
≥13	0.064	0.185	0.064	0.247

Source: Reference 8.

tion of base-year fractions of total HDT's in use nationwide by model year (to include diesel fractions thereof), and, second, the development of a set of diesel introduction rates.

Calculating Fractions of Annual HDT VMT by Model Year - To perform this step, nationwide urban HDD and HDG VMT for 1974[7] and AP-42 Supplement 8 VMT fractions[8] for diesel- and gasoline-powered HDT's are used to back-calculate the number of diesel- and gasoline-powered HDT's in use in urban areas nationwide. These vehicle-in-use data are then combined, and fractions of total HDT's by model year and diesel fractions of each model year are generated. Table 4-4 presents the vehicle-in-use fractions arrived at by this method.

Determining Diesel Vehicle Introduction Rates - Two different diesel introduction rates for each of the projection years are specified: a "best estimate" and a "maximum" case. Introduction rates for LDV's were obtained from the EPA Emission Control Technology Division (ECTD)[*] and are presented in Table 4-5. After discussion with ECTD personnel,[†] it was decided that these introduction rates should also be assumed to be representative of LDT's.

Basic data used to develop HDD introduction rates are from a recent Michigan Technological University (MTU) report

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[*] Memorandum from J.P. DeKany, U.S. EPA, re Request for an Air Quality Assessment of Particulate Emissions from Diesel-powered VEhicles, dated September 19, 1977.

[†] Communication with J. Somers, U.S. EPA, November 1977.

Table 4-4. BASE-YEAR FRACTIONS OF TOTAL HEAVY-DUTY TRUCKS IN USE NATIONWIDE (AND DIESEL FRACTIONS THEREOF)

Age, years	Fraction of total HDT's in use nationwide (1974) (urban only)	Fraction of model year (1974) HDT's that are diesel-powered
1	0.042	0.233
2	0.078	0.221
3	0.085	0.201
4	0.092	0.182
5	0.078	0.162
6	0.077	0.148
7	0.076	0.137
8	0.067	0.119
9	0.057	0.100
10	0.051	0.085
11	0.041	0.076
12	0.030	0.068
≥13	0.224	0.037

Table 4-5. CLASSIFICATION OF TRUCKS BY GVW

Truck class	GVW range, lb	MTU Projection Comments
1	< 6,000	"Low fractions are expected to occur with a high degree of probability... High fractions...are not very probable"
2A	6,000-8,500	
2B	8,500-10,000	"Low estimates of sales represent a slowly expanding economy... Moderate sales volume...expresses a steady or healthy growth... High truck sales projections are ...probable, if the economy grows exceptionally well and at the same time technical breakthroughs occur"
3	10,001-14,000	
4	14,001-16,00	
5	16,001-19,500	
6	19,501-26,000	
7	26,001-33,000	
8	> 33,000	

Source: Reference 9.

entitled The Development of an Emission and Fuel Economy Computer Model for Heavy-duty Trucks and Buses.[9] This model classifies truck population by gross vehicle weight (GVW) ranges and other relevant criteria.

The referenced report notes that past trends are no longer satisfactory for projecting diesel truck sales. General economic conditions, energy supply/demand constraints, and government fuel-economy, pollution, and safety regulations have placed the diesel engine "...in a position to dominate the future truck market because of its cost effectiveness in terms of power applications and utilization."[9]

Recognizing a great margin of uncertainty associated with making such projections, the authors of the MTU report generated three sets of new truck sales and three sets of diesel penetration fractions for each of the eight GVW classes listed in Table 4-5. Because these sales and penetration fractions were presented graphically, they are difficult to interpolate. They were, however, used to generate the sales and penetration fractions shown in Table 4-6. The penetration fractions are weighted by the sales data so as to produce cumulative penetration fractions for each projection year. For the purposes of this report, a "best estimate" introduction rate is defined to be low penetration fractions weighted by low sales estimates. A "high" rate is defined to be high penetration fractors weighted by high sales estimates.

Table 4-6. TRUCK SALES AND DIESEL PENETRATION FRACTIONS

Truck class	Vehicle Sales ($\times 10^6$) and Diesel Fractions[a]				
	Projection	1981	1983	1985	1990
2B	Low	0.14 (0.03)	0.14 (0.05)	0.14 (0.06)	0.15 (0.11)
	High	0.16 (0.14)	0.16 (0.32)	0.17 (0.57)	0.18 (0.97)
3	Low	0.00 (0.03)	0.01 (0.05)	0.01 (0.06)	0.01 (0.11)
	High	0.04 (0.14)	0.05 (0.32)	0.05 (0.57)	0.06 (0.97)
4	Low	0.00 (0.03)	0.00 (0.05)	0.00 (0.06)	0.00 (0.11)
	High	0.04 (0.14)	0.05 (0.32)	0.05 (0.57)	0.07 (0.97)
5	Low	0.00 (0.11)	0.00 (0.16)	0.00 (0.20)	0.00 (0.29)
	High	0.03 (0.20)	0.03 (0.47)	0.04 (0.79)	0.05 (1.00)
6	Low	0.17 (0.11)	0.18 (0.16)	0.19 (0.20)	0.21 (0.29)
	High	0.28 (0.20)	0.29 (0.47)	0.31 (0.79)	0.35 (1.00)
7	Low	0.02 (0.46)	0.02 (0.50)	0.02 (0.53)	0.02 (0.58)
	High	0.04 (0.70)	0.04 (0.80)	0.04 (0.89)	0.04 (1.00)
8	Low	0.10 (0.95)	0.10 (0.96)	0.10 (0.97)	0.11 (0.98)
	High	0.19 (1.00)	0.20 (1.00)	0.20 (1.00)	0.23 (1.00)
Total	Low	0.43 (0.33)	0.45 (1.31)	0.46 (0.33)	0.50 (0.64)
	High	0.78 (0.40)	0.82 (0.57)	0.86 (0.78)	0.98 (0.99)

[a] Figures in parentheses represent fractions of truck class sales which are projected to be diesel-powered.

Source: Reference 9.

Diesel introduction rates for the years in between the four projection years are determined through linear interpolation.

Table 4-7 summarizes the diesel vehicle introduction rates provided by ECTD and synthesized from the MTU report. The diesel introduction rates by model year shown in this table are used to modify the fractions of total vehicles in use shown in Tables 4-3 and 4-4. This is accomplished by multiplying the diesel fraction for a given model year times the fraction of vehicles in use that model year. These fractions are then used to perform the VMT fraction calculations described in AP-42, Supplement 8.[8] Tables A-1 through A-3 (in Appendix A) present details of the resulting VMT fractions for each of the projection years; Table 4-8 (in this section) summarizes this information.

At this point it is necessary to apply these fractions to the grid VMT developed previously. The result is a VMT total for each vehicle-engine class in each study area grid for two diesel-introduction-rate assumptions affecting each of the four projection years.

Assigning Emission Factors

Emission factors are available for two pollutants: particulate matter and BaP. For other pollutants (e.g., CO or HC), emission correction factors are available for such

Table 4-7. DIESEL VEHICLE INTRODUCTION RATES

	Share of new sales by model year			
	Light-duty vehicles and trucks		Heavy-duty trucks	
	(Percentages)			
	Best estimate	Maximum	Best estimate	Maximum
1975	0.5	0.5	28.0	28.0
1976	0.5	0.5	28.0	28.0
1977	0.5	0.5	28.0	28.0
1978	0.5	0.5	30.0	35.0
1979	2.0	5.0	31.0	36.0
1980	4.0	10.0	31.0	38.0
1981	6.0	15.0	31.0	40.0
1982	8.0	20.0	31.0	48.0
1983	10.0	25.0	31.0	57.0
1984	10.0	25.0	31.0	67.0
1985	10.0	25.0	33.0	78.0
1986	10.0	25.0	39.0	82.0
1987	10.0	25.0	45.0	86.0
1988	10.0	25.0	52.0	90.0
1989	10.0	25.0	58.0	94.0
1990	10.0	25.0	64.0	99.0

Table 4-8. FRACTION OF URBAN VMT BY MOBILE SOURCE CATEGORY IN PROJECTION YEARS

Mobile source category	1974	Fraction of urban VMT							
		1981		1983		1985		1990	
		Best est.	Max.	Best est.	Max.	Best est.	Max.	Best est.	Max.
Lt-duty gasoline vehicles	0.826	0.815	0.796	0.798	0.750	0.779	0.704	0.754	0.639
Lt-duty gasoline trucks	0.107	0.106	0.104	0.104	0.098	0.102	0.093	0.098	0.084
Hv-duty gasoline trucks	0.036	0.035	0.033	0.034	0.029	0.034	0.023	0.025	0.010
Lt-duty diesel vehicles	0.004	0.015	0.034	0.032	0.080	0.051	0.126	0.076	0.191
Lt-duty diesel trucks	0.001	0.002	0.004	0.004	0.010	0.006	0.015	0.010	0.024
Hv-duty diesel trucks	0.026	0.027	0.029	0.028	0.033	0.028	0.039	0.037	0.052

variables as average speed, ambient temperature, percent cold starts, truck weight, weight/power rates, and age deterioration. Such is not the case for particulate or BaP emissions. Further, the base emission factors for these two pollutants are based on fewer samples, hence can be expected to have much larger confidence intervals.

Recognizing the need for better emission factors, EPA generated the exhaust emission factors given in Table 4-9.[*][†][§] Except in the case of gasoline-powered light-duty vehicles and trucks, it is assumed that the emission factors will not vary from those given in Table 4-9. In the case of gasoline-powered light-duty vehicles and trucks, however, the effect of phasing out leaded fuel and phasing in innovative technology needs to be taken into account.

Two assumptions are made in calculating weighted emission factors for gasoline-powered light-duty vehicles and trucks in the four projection years:

- that all vehicles prior to the 1975 model year were noncatalyst and used leaded fuel, and
- that from 1975 on 70 percent of each new model year fleet will use catalysts and 30 percent will use catalysts with excess air.[9]

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[*] Memorandum from J.P. DeKany, U.S. EPA, re Request for an Air Quality Assessment of Particulate Emissions from Diesel-powered Vehicles, dated September 19, 1977.

[†] Communication with J. Somers, U.S. EPA, November 1977.

[§] Memorandum from J.P. DeKany, U.S. EPA, re Transmittal of Particulate Emission Factors for Heavy-duty Diesels, dated November 8, 1977.

Table 4-9. EXHAUST EMISSION FACTORS

Vehicle category	Emission factors	
	Particulates, g/VMT	BaP, μg/VMT
Light-duty gasoline-powered vehicles and trucks		
Catalyst	0.006	0.1
Catalyst (excess air)	0.015	0.1
Noncatalyst (leaded fuel)	0.25	1.0
Noncatalyst (unleaded fuel)	0.002	1.0
Heavy-duty gasoline-powered trucks		
Catalyst	0.02	0.3
Catalyst (excess air)	0.05	0.3
Noncatalyst (leaded fuel)	0.90	3.0
Noncatalyst (unleaded fuel)	0.007	3.0
Light-duty diesel-powered vehicles and trucks	0.5	1.0[a] 6.0[b]
Heavy-duty diesel-powered trucks	2.0	4.6[a] 24.6[b]

[a] Low estimate.

[b] High estimate.

The latter data are based on the further assumption that the technology used by Chrysler, General Motors, and Ford will be representative of the entire new fleet; that the current technological split between catalysts and catalysts with excess air will remain constant through 1990; and that the current technological split is as follows:[9]

	Share of new car fleet, percent	
Manufacturer	Catalyst	Catalyst (excess air)
Chrysler	90	10
General Motors	100	
Ford		100

When combined with 1974 new car sales data, these technological splits yield the 70/30 ratio described above.[10]

Weighted emission factors for a given year and diesel introduction rate assumption are calculated by using the age distribution data generated during the process of calculating VMT factors by vehicle-engine class. (Appendix A presents VMT factors.) Table 4-10 presents the resulting weighted emission factors for gasoline-powered light-duty vehicles and trucks.

Calculating Projection Year Exhaust Emissions

The emission factors just discussed are combined with the vehicle-engine class VMT by grid data to yield exhaust emissions by vehicle-engine class for each grid and each projection year. Tables 4-11 and 4-12 summarize the particulate and BaP emission totals for each projection year.

Table 4-10. WEIGHTED EMISSION FACTORS FOR GASOLINE-POWERED VEHICLES

	Particulates, g/VMT		BaP, µg/VMT	
	Lt-duty vehicle	Lt-duty trucks	Lt-duty vehicle	Lt-duty trucks
1974	0.25	0.25	1.0	1.0
1981				
Best est.	0.061	0.070	0.267	0.299
Max.	0.061	0.072	0.271	0.304
1983				
Best est.	0.035	0.047	0.178	0.219
Max.	0.035	0.049	0.183	0.227
1985				
Best est.	0.022	0.033	0.136	0.174
Max.	0.022	0.036	0.141	0.182
1990				
Best est.	0.017	0.026	0.119	0.149
Max.	0.017	0.029	0.123	0.158

Table 4-11. PROJECTED MOTOR VEHICLE EXHAUST EMISSIONS (PARTICULATES)[a]

(ton/yr)

Vehicle category	1974	1981		1983		1985		1990	
		Best est.	Max.	Best est.	Max.	Best est.	Max.	Best est.	Max.
Gasoline-powered									
Lt-duty vehicles	649	174	171	101	76	64	58	51	43
Lt-duty trucks	84	26	26	18	18	12	12	10	10
Hv-duty trucks	102	111	104	111	94	111	76	90	36
Subtotal	835	311	301	230	187	187	146	151	89
Diesel-powered									
Lt-duty vehicles	6	26	60	58	145	95	230	171	381
Lt-duty trucks	2	3	7	7	18	11	28	19	48
Hv-duty trucks	163	190	205	206	239	209	291	295	415
Subtotal	171	219	272	271	402	315	549	485	844
Total	1006	530	573	501	589	502	695	636	933

[a] "Best est." and "Max." refer to diesel introduction rate assumptions.

Table 4-12. PROJECTED MOTOR VEHICLE EXHAUST EMISSIONS (BaP)[a]

(ton/yr x 10^{-3})[b]

Vehicle category	1974	1981		1983		1985		1990	
		Best est.	Max.	Best est.	Max.	Best est.	Max.	Best est.	Max.
Gasoline-powered									
Lt-duty vehicles	2.596	0.763	0.758	0.513	0.497	0.395	0.369	0.358	0.315
Lt-duty trucks	0.336	0.111	0.111	0.082	0.080	0.066	0.063	0.058	0.053
Hv-duty trucks	0.340	0.369	0.348	0.369	0.315	0.380	0.257	0.299	0.120
Subtotal	3.272	1.243	1.217	0.964	0.892	0.841	0.689	0.715	0.488
Diesel-powered									
Lt-duty vehicles	0.013 (0.075)	0.053 (0.316)	0.119 (0.716)	0.116 (0.694)	0.289 (1.141)	0.190 (1.141)	0.470 (2.818)	0.303 (1.820)	0.762 (4.575)
Lt-duty trucks	0.003 (0.019)	0.008 (0.042)	0.014 (0.084)	0.014 (0.087)	0.036 (0.217)	0.022 (0.134)	0.056 (0.335)	0.040 (0.239)	0.096 (0.575)
Hv-duty trucks	0.376 (2.009)	0.426 (2.332)	0.469 (2.506)	0.466 (2.492)	0.549 (2.937)	0.480 (2.568)	0.669 (3.577)	0.680 (3.634)	0.955 (5.106)
Subtotal	0.392 (2.103)	0.497 (2.690)	0.602 (3.306)	0.596 (3.273)	0.874 (3.272)	0.692 (3.843)	1.195 (6.730)	1.023 (5.693)	1.813 (10.256)
Total	3.664 (5.375)	1.740 (3.933)	1.819 (4.523)	1.560 (4.237)	1.766 (5.783)	1.533 (4.684)	1.884 (7.419)	1.738 (6.408)	2.301 (10.744)

[a] "Best est." and "Max." refer to diesel introduction rate assumptions.

[b] Figures in parentheses represent values obtained with high BaP emission factor.

4.3 PROJECTED IMPACT OF DIESEL EMISSIONS ON AIR QUALITY

The impact of diesel emissions on ambient TSP concentrations is predicted by using the calibrated AQDM discussed earlier. This is done by running the AQDM for each projection year, using only diesel emissions as input. The impact of diesels on ambient BaP concentrations is determined similarly, but a ratio of BaP to particulate emissions is also applied to the calculations for each projection year. Table 4-13 presents the ratios used for each projection case.

Total Suspended Particulate Concentrations

The maximum annual TSP concentration from diesel-powered vehicles in 1974 (0.35 $\mu g/m^3$) occurred in the immediate downtown area. This rather low maximum concentration suggests that diesels contributed a relatively small amount of particulate matter that year.

The emission data presented earlier, however, indicate that TSP concentrations attributable to diesels will increase through 1990. Table 4-14 summarizes the predicted changes in regional concentrations over the projection period. The regional TSP concentrations resulting from diesel usage are projected to increase steadily to a high in 1990 of either 0.96 or 1.73 $\mu g/m^3$ (annual geometric mean), depending upon the assumed rate of diesel introduction. The higher value constitutes 2.3 percent of the primary national ambient air quality standard (NAAQS) for TSP.

Table 4-13. RATIO OF BaP TO PARTICULATE EMISSIONS

(Diesels only)

Year	Low BaP	High BaP
1974	2.2864×10^{-6}	12.2866×10^{-6}
1981		
Best estimate	2.2592×10^{-6}	12.2618×10^{-6}
Max. diesel	2.2261×10^{-6}	12.2259×10^{-6}
1983		
Best estimate	2.2271×10^{-6}	12.2269×10^{-6}
Max. diesel	2.1783×10^{-6}	12.1778×10^{-6}
1985		
Best estimate	2.1989×10^{-6}	12.1984×10^{-6}
Max. diesel	2.1575×10^{-6}	12.1569×10^{-6}
1990		
Best estimate	2.1895×10^{-6}	12.1879×10^{-6}
Max. diesel	2.1474×10^{-6}	12.1465×10^{-6}

Table 4-14. PROJECTED REGIONAL ANNUAL AVERAGE CONCENTRATIONS OF TSP FROM DIESEL EXHAUST FOR TEST CITY.

Year	Diesel Growth Case	
	Best Est.	Max. Growth
	µg/m^3	
1974	0.35	
1981	0.45	0.56
1983	0.57	0.83
1985	0.65	1.13
1990	0.96	1.73

The method for predicting BaP concentrations attributable to diesels differs from that described for TSP only in that BaP concentrations are indirectly modeled by AQDM. It is assumed that a ratio of BaP to particulate emissions can be applied to predicted TSP concentrations to yield predicted BaP concentrations for each grid in a given year. The ratio changes from year to year because of variations in emission factors and vehicle category mix.

The ratios presented in Table 4-15 are calculated by defining the VMT/yr (see Table 4-8), the particulate emission factor, and the BaP emission factor for each diesel vehicle category. Two BaP emission factors are used for each diesel type to correspond with the factors given in Table 4-10. The data are combined and totaled to yield total particulate and BaP emissions from diesels, and the ratios between the two totals are developed. The process is repeated for each projection year.

4.4 ASSESSING POPULATION EXPOSURE

The difficulties involved in assessing exposure of a given population to varying concentrations of a pollutant are well documented in the air pollution control literature.[11] Two examples are cited below:

Table 4-15. PROJECTED REGIONAL ANNUAL AVERAGE CONCENTRATIONS OF BaP FROM DIESEL EXHAUST FOR TEST CITY

Projection case		Regional annual geometric mean BaP cone, ng/m^3 x 10^{-3}	
Year	Diesel growth case	Emission factor case	
		Low	High
1974		0.8	4.3
1981	Best est.	1.0	5.5
1981	Max. growth	1.2	6.8
1983	Best est.	1.3	6.9
1983	Max. growth	1.8	10.1
1985	Best est.	1.4	7.9
1985	Max. growth	2.9	13.8
1990	Best est.	2.1	11.7
1990	Max. growth	3.7	21.1

- The representativeness of measured air quality data is uncertain. Data obtained in monitoring a pollutant like carbon monoxide may be representative of little more than exposure at the exact location of the monitor. Conversely, data on TSP obtained with a hi-vol sampler in a rural area may well be representative of hundreds of square kilometers.
- People are mobile rather than stationary, tending to live in one place, work in another, and travel often among various points. Thus, the exposure of people to a given pollutant may differ significantly from the concentrations measured at any one site.

Both of these limitations are especially serious when averaging periods are short-term (1, 3, or 8 hours). When averaging periods are longer, both concentrations and exposures tend to homogenize. In assessments of particulates and BaP, the focus is primarily on annual concentrations or those representing longer-term averaging periods. Thus, in this report it is assumed that the place of residence (as defined by the U.S. Bureau of Census and similar data) is generally representative of exposure to annual concentrations. Residences located near roadways are an exception. It cannot be assumed that measured air quality data are representative of air quality at residences near heavily travelled roadways. On the contrary, recent empirical data clearly indicate that TSP concentrations increase as the slant distance from roadways decreases, and that TSP concentrations increase with increasing traffic volume.[12]

The exposure of persons living in such locations cannot be assessed in the test city, however, because no data are available on the number of people living at x distance from roadways of y traffic.

Exposure of the test city population to varying levels of TSP and BaP is assessed by assigning locally generated data on 1970 origin-destination (OD) zone population to a grid system established about the AQDM receptor network.[13] Thus 165 grids, 2 by 2 km, are centered upon the 165 AQDM receptors. The OD zone populations are assigned to the grids on the basis of land area by assuming that populations are uniformly distributed within each OD zone.

It is assumed that the total population and its distribution in the test city will not change from 1970 to 1990. Such an assumption is necessary to minimize the computation required to generate projections. This assumption should not introduce significant error, because the rate and distribution of population growth are expected to vary greatly from city to city.

The number of persons exposed to varying concentrations is predicted by combining these population data with the concentrations predicted by AQDM for the projection years.

The AQDM program produces the TSP concentration at a series of grid points throughout the urbanized population area, but it does not indicate the extremes in concentration levels to which the population may be exposed. Further, no population exposure data are available that account for distances from roadways. This analysis attempts to predict a range of population exposure; therefore the procedure incorporates a distribution that estimates the upper exposure. The dosage spectrum distribution developed by Horie and Stern[11] for data from the New York-New Jersey-Connecticut Tri-State Region is used for this purpose. Dosage extremes are estimated from a mean value for a given area, assuming a population evenly distributed over the area. This dosage relationship is represented mathematically:

$$S(\bar{D}) = \int_r N(r,D)dr/Ao$$

where $S(\bar{D})$ is the dosage spectrum
r is the receptor site
Ao is the area under consideration
$N(r,D)$ is a threshold function such that
$N(r,D) = 1$ if $D(r) > \bar{D}$
$N(r,D) = 0$ otherwise
$\bar{D}$ is the dosage threshold[11]

Simply stated, this equation presents the fraction of a total area $S(\bar{D})$ that is polluted more than $\bar{D}$. Figure 4-3 shows this relationship for data from the Tri-State Region. These data allow an extrapolation of the TSP concentration at highest exposure level.

A dosage spectrum is generated from each grid point concentration. The dosage spectra-population data over the

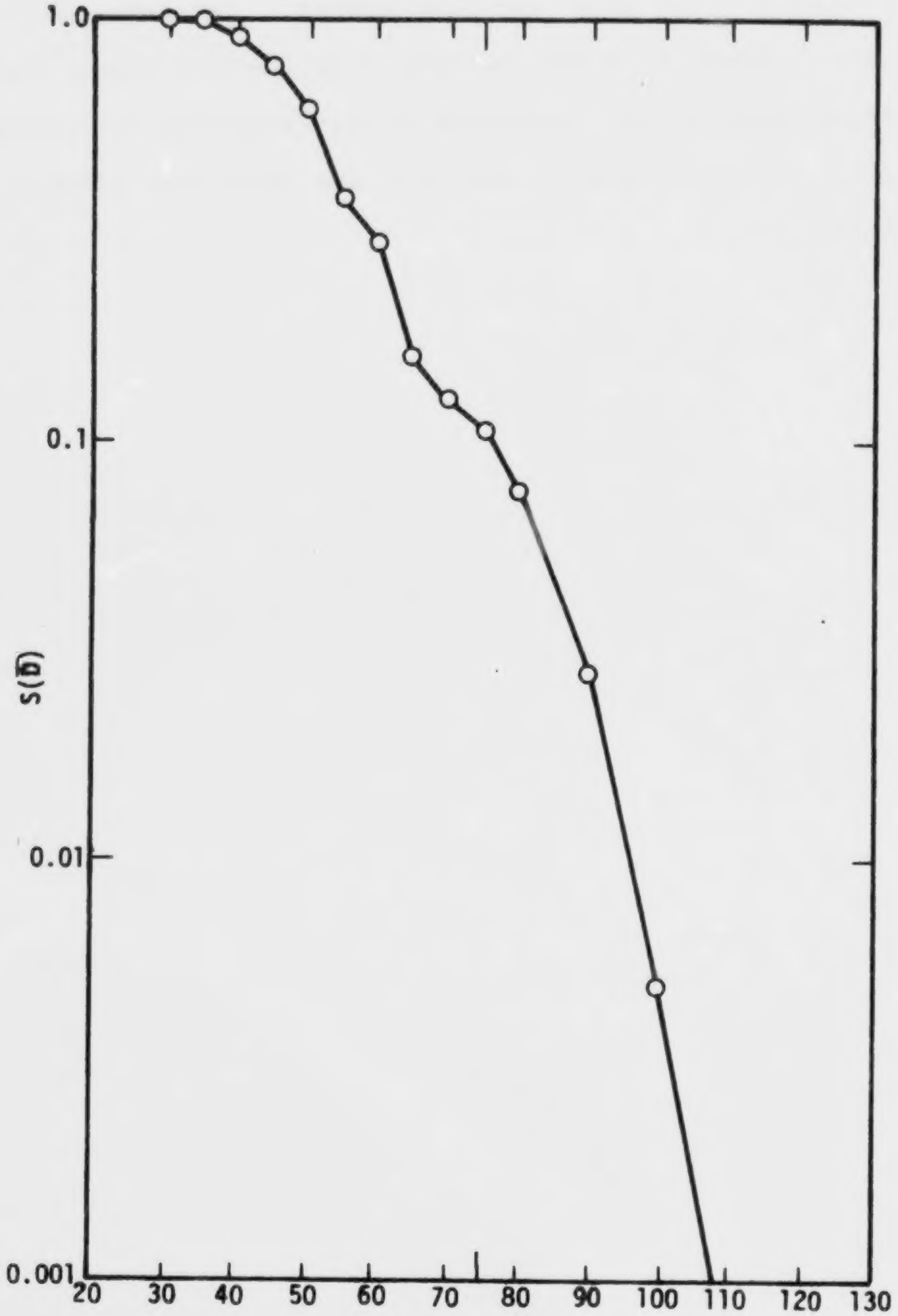

Figure 4-3. Dosage spectrum distribution in the Tri-State Region (19).

entire gridded area are then summed. The Horie and Stern[11] relationship is based on data from the Tri-State Region. These data do not represent either national or Kansas City data; however this is the only one data base readily available.

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5.0 ESTIMATES OF POPULATION EXPOSURES TO TSP AND BaP

Estimates of exposures of the national population to TSP and BaP from diesel-powered vehicles are based on the Kansas City data and on national trends. Estimates of TSP and BaP concentrations expected to occur near roadways are also presented on the basis of regional maximum short-term (1-hour and 24-hour) and annual measurements. The correlation methods and results of the analyses are discussed in this section.

5.1 NATIONAL POPULATION IMPACT

5.1.1 TSP Dosage Analysis

Because the major constraint built into this analysis is that a population-dose relationship is available only for the test city, a method was sought to exprapolate the test city dose data to all SMSA's.

Several approaches were evaluated for characterizing the national population with regard to total TSP exposure. This list is by no means exhaustive, and because of time limitations imposed on development of this report, consideration was given only to those variables that appeared most likely to correlate with the TSP level and for which a comprehensive empirical data base was readily available.

i) Annual geometric mean concentrations of TSP were analyzed at ambient monitoring sites in 15 cities of various sizes. Information from the National Air Data Bank (NADB) was correlated with data on SMSA population, urbanized SMSA population density, and percentage of urban blue-collar workers. The percentage of blue-collar workers was included in an effort to characterize the degree of industrialization in an urban area that could have an impact on the TSP level. Values for these three parameters are readily available from census compilations, and information at the census tract level should best characterize the individual monitoring station location. Correlations of TSP with these three parameters were very poor, however, probably because the monitoring sites often do not reflect the average TSP level in a census tract and the three parameters do not indicate the types of particulate sources in an SMSA. Thus, this approach was rejected.

ii) An effort was made to analyze dosage in terms of the annual TSP loading in selected urbanized counties. Data from the National Emissions Data System (NEDS) are readily available for point sources in all U.S. counties, but data on area sources are not systematically compiled or updated. Because NEDS considers roadways as area sources, this approach was rejected.

iii) Finally, the annualized geometric mean TSP levels for all monitoring stations reporting to NADB were averaged, and the average level was correlated with SMSA population and urbanized SMSA population density. The percent of urban blue-collar workers did not correlate with TSP and was excluded from consideration. The TSP data for selected cities were the most recent year's values reported to the NADB. This approach was selected as the means of characterizing the exposure of the total U.S. population to TSP. Averaging all monitoring station TSP levels in an SMSA smoothed out the data and reduced the impact of local conditions on single station analysis attempted in i) above.

The annual TSP levels from monitoring stations in 66 SMSA's were used to develop the correlations. These data are presented in Appendix B. The relationship based on correlation of TSP with SMSA population and urban population density is shown in Figure 5-1.

In development of the exposure relationships, the U.S. population is summed by SMSA for the 4 target years, within ranges of population and population density. The summed data in 15 cells are shown in Table 5-1. Since the regression line correlations in Figure 5-1 are not good, these data are presented in a two-dimensional array with each cell given a TSP mean and standard deviation to characterize the

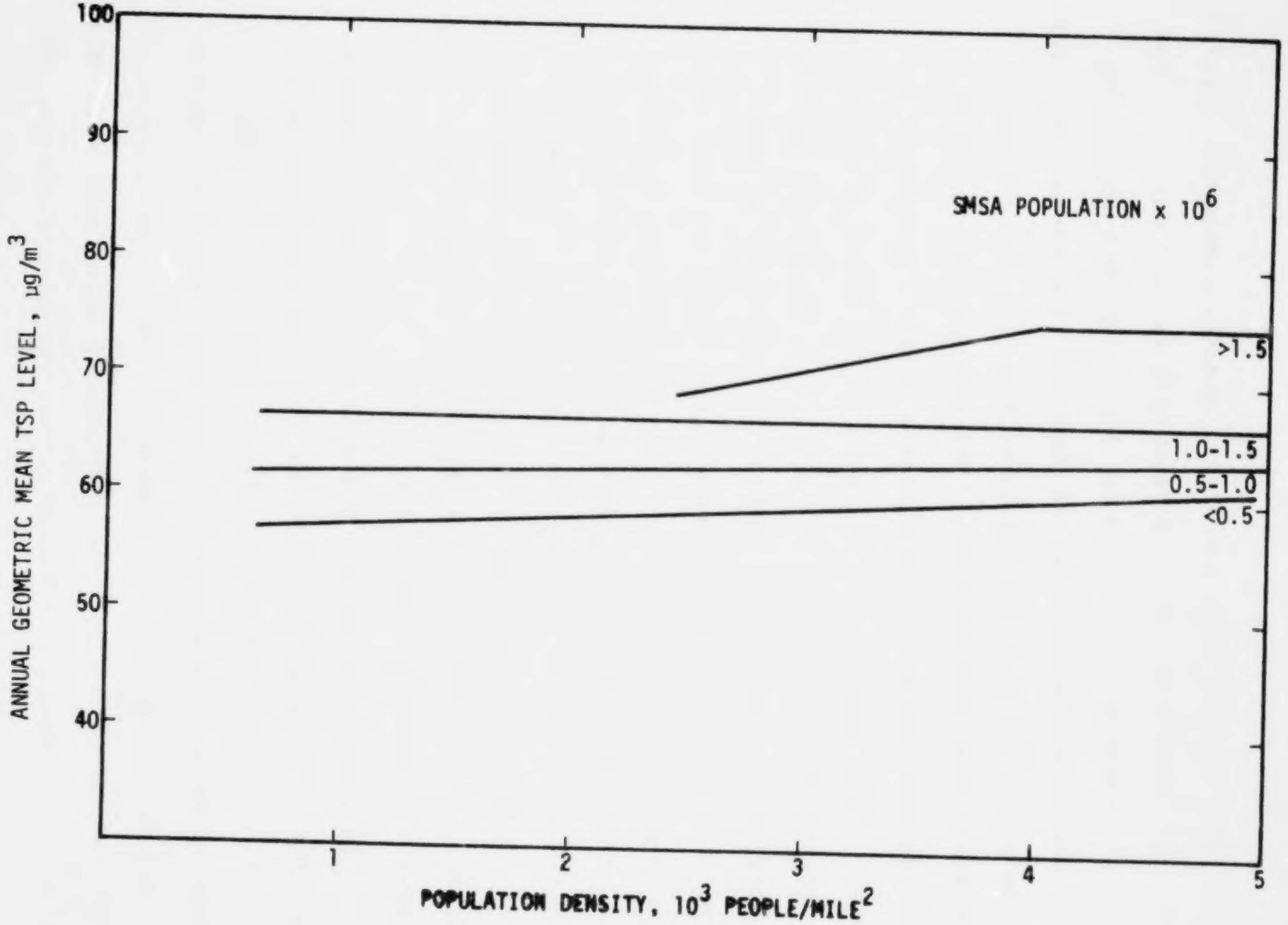

Figure 5-1. Correlation of average NASN annual geometric mean TSP levels for selected SMSA's versus SMSA population and population density.

Table 5-1. DISTRIBUTION OF U.S. POPULATION BY SMSA POPULATION RANGE AND POPULATION DENSITY FOR PROJECTION YEARS - NATIONAL SMSA POPULATIONS

Urbanized population density 10^3 people/mi^2	Cell no.	Metropolitan population 10^6 people	Millions of people in each SMSA population group							
			1981		1983		1985		1990	
			U[a]	T[b]	U	T	U	T	U	T
<2	1	<0.5	4.984	7.074	5.079	7.214	5.179	7.356	5.452	7.743
	2	0.5-1.0	2.651	2.927	2.741	3.033	2.828	3.129	3.061	3.388
	3	1.0-1.5	0.687	1.342	0.702	1.372	0.718	1.402	0.758	1.481
2-2.99	4	<0.5	11.267	15.847	11.505	16.183	11.321	16.004	11.269	15.844
	5	0.5-1.0	9.153	11.286	9.390	11.574	9.007	11.322	9.393	11.990
	6	1.0-1.5	4.720	5.530	3.520	4.167	4.643	5.317	3.029	3.618
	7	>1.5	5.049	5.706	6.564	7.430	6.789	7.686	10.219	11.540
3-3.99	8	<0.5	5.916	9.211	6.017	9.369	6.136	9.537	5.804	8.944
	9	0.5-1.0	8.615	10.742	7.902	9.968	7.256	9.174	6.676	8.669
	10	1.0-1.5	4.498	5.126	5.566	6.323	3.779	4.471	5.637	6.818
	11	>1.5	11.338	13.309	11.575	13.590	14.608	16.942	15.548	18.019
4+	12	<0.5	1.756	2.429	1.852	2.540	1.835	2.532	1.942	2.670
	13	0.5-1.0	0.412	0.697	0.418	0.707	0.424	0.717	0.440	0.744
	14	1.0-1.5	2.819	3.509	2.867	3.572	2.913	3.633	3.036	3.795
	15	>1.5	55.826	60.667	56.895	61.846	58.199	63.223	61.716	66.565

[a] U - urbanized part of SMSA population.

[b] T - total urbanized population.

data scatter. Table 5-2 presents the annual geometric mean TSP and intercity standard deviations corresponding to each combination of SMSA population and population density from the data in Figure 5-1. Where cells have few representative test cities, values are extrapolated from Figure 5-1 and from values for adjoining cells in Table 5-2.

The TSP-population exposure distribution described in Section 4.4 is applied to each of the 15 population cells. Further, each cell population is divided into five equal fractions using the cell mean and standard deviation:

Population cell fraction	Fraction of cell population	Mean of subfraction
1	0.20	$\bar{X}$ - 1.28 S.D.
2	0.20	$\bar{X}$ - 0.538 S.D.
3	0.20	$\bar{X}$
4	0.20	$\bar{X}$ + 0.53 S.D.
5	0.20	$\bar{X}$ + 1.28 S.D.

The population distribution of each population subcell is estimated by multiplying the Kansas City population-exposure distribution times the subcell mean divided by the Kansas City mean. The Kansas City mean is the mean TSP level for all the monitoring stations, which in 1976 was 63.6 $\mu g/m^3$. A total population exposure range is determined by applying the appropriate population data from Table 5-1 to the individual subcell exposure distributions and summing all the subcell TSP versus population relationships.

Table 5-2. SUMMARY OF TSP DATA FROM TEST CITY MONITORING STATIONS

Population x 10^6		Population density - urbanized, 10^3 people/mi^2			
		<2	2-<3	3-<4	4
<0.5	Mean[a]	57.7	58.7	59.5	60.5
	S.D.[b]	3.0	3.1	2.7	2.7
	N[c]	4	17	7	2
0.5-1.0	Mean	62.0	62.5	63.0	63.2
	S.D.	2.5	2.6	4.2	4.2
	N	1	6	8	1
1.0-1.5	Mean	66.5	66.5	66.5	66.5
	S.D.	3.6	3.6	4.0	4.3
	N	0	4	3	2
>1.5	Mean	d	69.0	73.0	75.0
	S.D.		3.6	3.6	4.4
	N		2	2	7

[a] Geometric mean TSP level in $\mu g/m^3$.

[b] Standard deviation of mean.

[c] Actual number of cities in test data analyzed in each population region.

[d] No population in this range.

The diesel particulate dose distribution developed for Kansas City was projected for the national population, assuming correlations similar to those developed for SMSA population and population density versus TSP.

The overall national population dose distribution procedure is summarized in Figure 5-2.

5.1.2 Population Exposures to TSP

Table 5-3 presents estimates of population exposure relationships to TSP for each projection case. In every case, the distribution consists of the minimum annual geometric mean diesel emission particulate concentration to which increments of the population are exposed. In both best estimate and maximum diesel vehicle growth cases, the concentrations are shown to increase progressively between 1981 and 1990. Emphasis is placed on the most exposed fraction of the population because the attributable health effects are expected to be more pronounced in this group. In none of the cases is the diesel fraction of total TSP emissions large enough to allow a meaningful graphic representation of its relative contribution to the total TSP level. Table 5-4 does show the contribution of diesels to total population exposure as a function of TSP range. The values on the table represent the percent of the total population exposed to different TSP concentrations attrib-

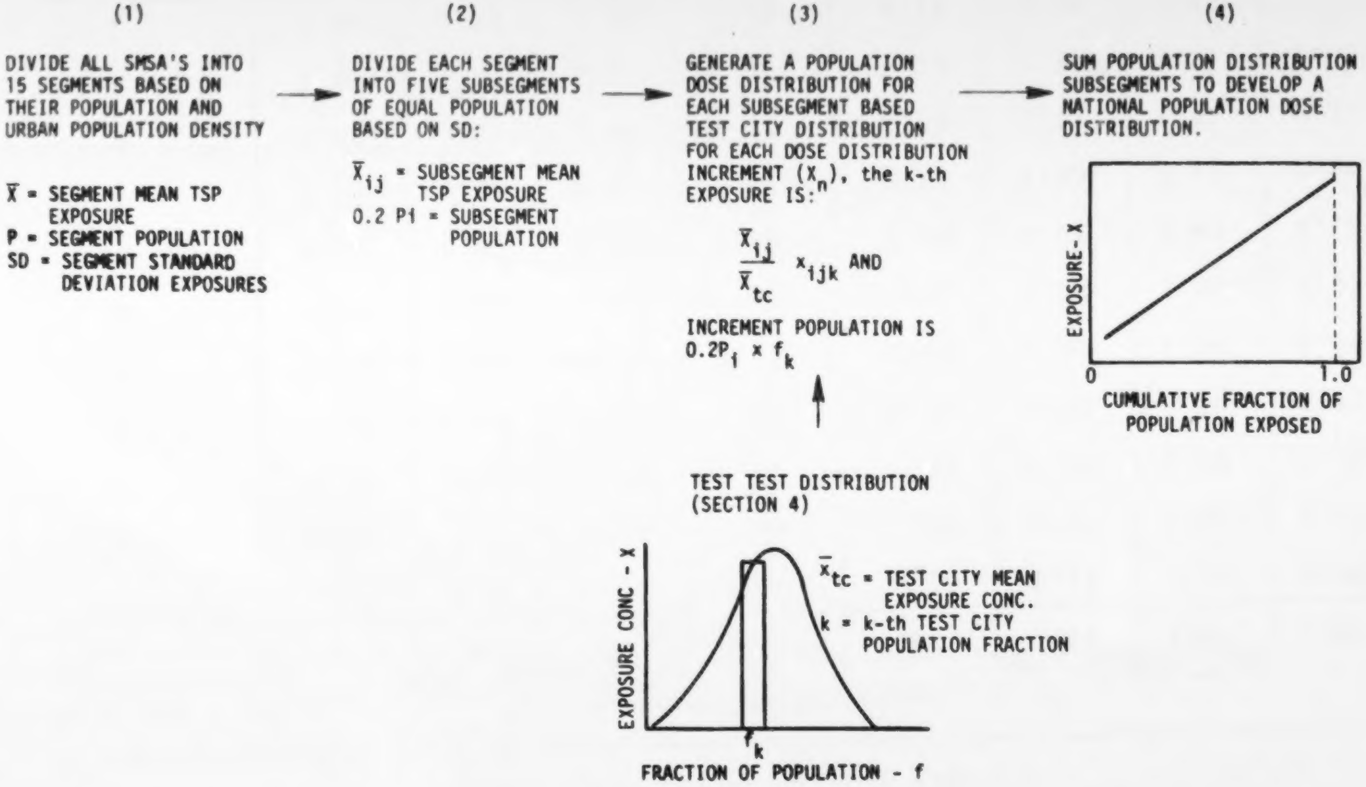
(1)
DIVIDE ALL SMSA'S INTO 15 SEGMENTS BASED ON THEIR POPULATION AND URBAN POPULATION DENSITY
$\overline{X}$ = SEGMENT MEAN TSP EXPOSURE
P = SEGMENT POPULATION
SD = SEGMENT STANDARD DEVIATION EXPOSURES
(2)
DIVIDE EACH SEGMENT INTO FIVE SUBSEGMENTS OF EQUAL POPULATION BASED ON SD:
$\overline{X}_{ij}$ = SUBSEGMENT MEAN TSP EXPOSURE
0.2 Pi = SUBSEGMENT POPULATION
(3)
GENERATE A POPULATION DOSE DISTRIBUTION FOR EACH SUBSEGMENT BASED TEST CITY DISTRIBUTION FOR EACH DOSE DISTRIBUTION INCREMENT (X_n), the k-th EXPOSURE IS:
$\frac{\overline{X}_{ij}}{\overline{X}_{tc}} x_{ijk}$ AND
INCREMENT POPULATION IS $0.2P_i \times f_k$
(4)
SUM POPULATION DISTRIBUTION SUBSEGMENTS TO DEVELOP A NATIONAL POPULATION DOSE DISTRIBUTION.
EXPOSURE- X
0
1.0
CUMULATIVE FRACTION OF POPULATION EXPOSED
TEST TEST DISTRIBUTION (SECTION 4)
EXPOSURE CONC - X
$\overline{x}_{tc}$ = TEST CITY MEAN EXPOSURE CONC.
k = k-th TEST CITY POPULATION FRACTION
f_k
FRACTION OF POPULATION - f

Figure 5-2. Information flow diagram for the development of the population TSP dose relationship for each projection case.

Table 5-3. ESTIMATED ANNUAL EXPOSURE CONCENTRATIONS OF TSP FROM DIESEL VEHICLE EXHAUST.

Millions of people Exposed	Exposure Concentration, $\mu g/m^3$							
	Best Estimate Case				Max. Growth Case			
	1981	1983	1985	1990	1981	1983	1985	1990
100	0.24	0.26	0.31	0.50	0.25	0.39	0.58	0.88
50	0.34	0.38	0.44	0.69	0.38	0.57	0.81	1.23
25	0.42	0.48	0.56	0.87	0.47	0.72	1.02	1.55
10	0.52	0.59	0.71	1.08	0.58	0.90	1.26	1.91
8	0.54	0.61	0.74	1.12	0.60	0.93	1.30	1.98
6	0.57	0.64	0.78	1.17	0.63	0.98	1.36	2.07
5	0.58	0.65	0.80	1.20	0.65	1.01	1.40	2.12
4	0.59	0.67	0.84	1.22	0.66	1.03	1.42	2.16
3	0.61	0.69	0.87	1.25	0.68	1.07	1.46	2.21
2	0.63	0.70	0.93	1.29	0.70	1.10	1.51	2.29
1	0.66	0.73	1.02	1.36	0.72	1.16	1.59	2.41

Table 5-4. PERCENT OF POPULATION EXPOSURE TO TSP ATTRIBUTABLE TO DIESEL EXHAUST EMISSIONS.

TSP Conc, $\mu g/m^3$	TSP - All sources Millions of people exposed[a]	Best Estimate Case				Max. Growth Case			
		1981	1983	1985	1990	1981	1983	1985	1990
40	152	0.1	0.1	0.2	0.2	0.1	0.2	0.3	0.2
50	134	0.3	0.4	0.7	1.2	0.4	0.9	1.2	1.5
60	103	0.3	0.3	0.8	1.8	0.3	1.2	2.5	3.0
70	74	0.2	0.3	0.8	1.6	0.3	1.1	2.3	3.3
80	52	0.8	0.8	0.9	1.7	0.8	1.7	2.4	3.3
90	36	1.4	1.6	1.9	2.3	1.6	2.4	2.6	4.2
100	24	2.5	2.7	3.2	3.2	2.7	3.2	3.6	5.8
110	14	3.6	3.8	3.8	3.8	3.8	3.8	4.4	8.8
120	8	3.4	3.7	3.7	3.8	3.7	3.9	4.3	10.1
130	4	2.8	3.2	3.2	3.4	3.2	3.4	3.5	8.3

[a] Data based on 1981, best estimate diesel growth case.

utable to diesel exhaust. Although no correlation was found between total TSP levels and diesel particulate contribution, this table clearly shows that the higher the TSP concentrations, the greater the diesel-contributed percent impact is expected to be on the total population exposed. Diesel vehicles contribute the greatest percentage at total TSP levels between 110 and 120 μg/m^3 (3.6 to 10.2 percent).

National TSP exposure relationships are also normalized to show the population exposed to TSP concentrations exceeding the national standard (75 μg/m^3 annual). Table 5-5 presents this information. This table also presents the diesel vehicle contribution for each projection case. These estimates are based on the following projected population growth data:[1]

	Population x 10^6	
	SMSA	Total
1981	155.4	261.0
1983	158.9	266.3
1985	162.4	277.2
1990	171.8	297.2

The 1990 maximum diesel growth case shows the highest diesel TSP contribution (2.2 million of the total 72.3 million people exposed to greater than the TSP standard). Thus it appears that the most sensitive indicator of the impact of diesel TSP is obtained by matching the diesel TSP contribu-

Table 5-5. ESTIMATED POPULATION EXPOSED TO MORE THAN THE FEDERAL STANDARD FOR TSP.

Projection year	Millions of people exposed to more than 75 $\mu g/m^3$ Diesel vehicle growth case			
	Best estimate		Maximum growth	
	Total exposed	Diesel contrib.	Total exposed	Diesel contrib.
1981	62.7	0.4	62.8	0.4
1983	64.3	0.4	64.7	0.8
1985	66.4	0.6	67.3	1.5
1990	71.1	1.0	72.3	2.2

tion to the total TSP level at high exposure locations, as presented in Table 5-4.

5.1.3 BaP Dosage Analysis

Data are not adequate to attempt a comprehensive inventory of BaP emission sources in Kansas City. Thus national BaP exposure data are used, and the contribution of diesel vehicles is added.

Total BaP exposure is estimated by summing the exposure of population to BaP emitted from coke ovens and BaP exposure in locations without impacting coke ovens. The reason for this approach is that NASN data on BaP concentrations show that in cities with coke ovens the average BaP concentration is 1.21 ng/m^3, with a range of 0.3 to 4.7 ng/m^3 in 21 samples, whereas in cities without coke ovens the average is 0.35 ng/m^3, with a range of 0.03 to 0.90 ng/m^3 in 15 samples.[2]

Locations for which coke ovens have a significant impact are taken from a recent report from Stanford Research Institute (SRI),[2] in which population exposures to BaP emitted from coke ovens are estimated by determining the populations within a series of concentric rings around each coke oven and estimating the annual average BaP concentration by use of monitoring data and an extrapolative modeling technique. Impact of BaP from other sources is also included. The overall BaP exposure relationship developed by SRI is shown in Table 5-6.

The BaP impact not attributable to coke ovens is based on data from NASN's urban stations at locations without coke ovens. The annual average BaP concentrations reported by NASN are presented in Table 5-7. The mean concentration is 0.35 ng/m^3, with a standard deviation of 0.21, based on data from 15 cities. In generation of a distribution from these data it is assumed that the concentration is normally distributed. This analysis, shown in Table 5-8, is based on the total 1976 U.S. urbanized population of 144.95 million people minus 17.1 million exposed to coke oven emissions.

The diesel component of the total population exposure to BaP is based on diesel BaP relationships developed from the Kansas City emission inventory analysis. Each projection case for BaP includes 4 projection years, each with a best estimate and maximum diesel growth case and low and high diesel BaP emission factors. For each case the BaP concentration is correlated with population density for 165 grid points. Grid areas, all of known population, are divided into four groups as a function of population density:

Table 5-6. ANNUAL AVERAGE EXPOSURE CONCENTRATIONS OF BaP EMITTED BY COKE OVENS[2]

Subgroup concentration range, ng/m^3	Cumulative number of people exposed	
	Background plus coke oven emissions	Coke oven emissions only[a]
95-100	1,800	1,800
50-55	2,670	2,670
45-50	2,720	2,720
40-45	4,220	4,220
35-40	5,920	5,920
30-35	9,320	8,320
25-30	14,120	9,920
20-25	19,120	18,920
15-20	82,820	82,620
10-15	630,220	219,920
8-10	705,320	662,620
6-8	981,020	798,920
5-6	1,097,720	995,220
4-5	1,345,920	1,182,320
3-4	3,069,020	1,971,620
2-3	7,335,620	3,216,820
1-2	15,148,620	8,243,520
0.5-1	16,754,020	12,923,120
0.2-0.5	17,106,620	17,106,620

[a] Number exposed to indicated concentration or more.

Table 5-7. ANNUAL AVERAGE AMBIENT BaP CONCENTRATIONS AT NASN URBAN STATIONS WITHOUT COKE OVEN IMPACT

City	BaP concentration, ng/m^3	Population $x\ 10^6$	Urban population density range[a]
Montgomery	0.3	0.14	2
New York	0.9	11.6	4
Toledo	0.4	0.49	2
Charleston, WV	0.5	0.16	2
St. Louis	0.3	1.88	4
Spokane	0.6	0.23	3
Jacksonville	0.4	0.53	1
Honolulu	<0.1	0.44	3
Baton Rouge	0.1	0.25	2
New Orleans	0.2	1.96	4
Duluth	0.3	0.14	1
Houston	0.2	1.68	3
Norfolk	0.2	0.67	2
Seattle	0.4	1.24	3
St. Paul	0.4	1.70	2

[a] Population density ranges
1 is 0-1.99 x 10^3 people/mi^2
2 is 2-2.99 x 10^3 people/mi^2
3 is 3-3.99 x 10^3 people/mi^2
4 is 4 or more x 10^3 people/mi^2

Table 5-8. POPULATION EXPOSURE TO BaP IN URBAN AREAS WITHOUT COKE OVEN IMPACT

BaP concentration, ng/m^3	Z^a	Fraction of population less than X concentration	% of population in interval	Population in conc. interval x 10^6
0.90+	<2.75	0.997	0.003	0.38
0.8-0.9	2.25-2.75	0.988	0.009	1.15
0.7-0.8	1.75-2.25	0.960	0.028	3.58
0.6-0.7	1.25-1.75	0.894	0.066	8.44
0.5-0.6	0.75-1.25	0.773	0.121	15.47
0.4-0.5	0.25-0.75	0.599	0.174	22.25
0.3-0.4	-0.25-0.25	0.401	0.198	25.31
0.2-0.3	-0.75-0.25	0.227	0.174	22.25
0.1-0.2	-1.25-0.75	0.106	0.121	15.47
<0.1	<-1.25	0.040	0.106	

[a] $Z = \frac{X-\bar{X}}{\sigma}$ for a given concentration level X where

$\bar{X}$ is the mean (0.35 ng/m^3) and σ is the standard deviation on the population sample.

Group	Population density, 1000 people/mi^2
1	<2
2	2 - 2.99
3	3 - 3.99
4	4 or more

The mean and standard deviations of the BaP values are determined for each group. To develop a more sensitive prediction of high BaP exposures, each group is then divided into five equal population groups, and a subgroup mean is estimated from the group mean and standard deviations. This approach is identical to that used to generate subcell TSP groups in Section 5.1.2.

A population exposure relationship for diesel BaP is also developed from the Kansas City data for the 165 grid points. An exposure distribution is developed by summing individual grid area populations for a series of diesel BaP concentration ranges.

National SMSA populations for each projection year are summed within four urban population density ranges. The four groups are then divided into the five equal subgroups described above. A population-versus-dose distribution is developed for each subgroup within each case by multiplying the Kansas City exposure distribution by the ratio of the subgroup over the Kansas City mean. Subgroups are then summed to produce the overall national population distributions.

5.1.4 Population Exposure to BaP

The estimate of total U.S. exposure to BaP is presented in Table 5-9. The values are based primarily on 1975 BaP monitoring data and 1976 population estimates. There are no projections to 1981-1990, because although ambient BaP concentrations are tending downward,[3] no reliable projections are available. The decline in BaP concentration between 1966 and 1975 has more than compensated for the increase in urbanized U.S. population.

Table 5-10 shows the population exposure for the 16 BaP projection cases. The concentration range is far below the lowest range of total BaP exposures presented in Table 5-9. The highest exposure case (1990, with maximum diesel fleet growth and high emissions) shows the 1 million most-exposed people in the nation being exposed to 0.034 ng/m^3, whereas Table 5-9 shows 116 million exposed to 0.2 to 0.4 ng/m^3 or greater. A more sensitive means of estimating ambient BaP exposure would help to produce a more realistic assessment of the diesel contribution to ambient BaP; however, the present paucity of empirical data appears to preclude further refinement of the analysis.

5.2 PROJECTED MAXIMUM IMPACT OF DIESEL EMISSIONS ON AIR QUALITY

Larsen's statistical transforms and Record's empirical relationships are used to predict the regional maximum 24-

Table 5-9. ESTIMATED TOTAL POPULATION DOSAGE OF BaP IN 1976

BaP conc., ng/m^3	Population exposure to concentration greater or equal to BaP level shown			
	Coke oven exposure[1]	Urban exposure x 10^6	Total x 10^6	% of population
95-100	1,800		0.002	<0.1
50-55	2,670		0.003	<0.1
45-50	2,720		0.003	<0.1
40-45	4,220		0.004	<0.1
35-40	5,920		0.006	<0.1
30-35	9,320		0.009	<0.1
25-30	14,120		0.014	<0.1
20-25	19,120		0.019	<0.1
15-20	82,820		0.083	<0.1
10-15	630,220		0.630	0.3
8-10	705,320		0.705	0.3
6-8	981,020		0.981	0.5
5-6	1.098 x 10^6		1.098	0.5
4-5	1.346 x 10^6		1.346	0.6
3-4	3.069 x 10^6		3.069	1.5
2-3	7.336 x 10^6		7.336	3.5
1-2	15.149 x 10^6		15.149	7.2
0.8-1	15.791 x 10^6	1.534	17.325	8.3
0.6-0.8	16.433 x 10^6	13.552	29.985	14.3
0.4-0.6	16.873 x 10^6	51.268	68.141	32.4
0.2-0.4	17.107 x 10^6	98.828	115.935	55.2

Table 5-10. ANNUAL AVERAGE EXPOSURE CONCENTRATIONS OF BaP FROM DIESEL EXHAUST EMISSIONS.

a) Low diesel exhaust emission rate case

Population exposed millions	Exposure level - $ng/m^3 \times 10^{-3}$							
	Best estimate growth case				Max. growth case			
	1981	1983	1985	1990	1981	1983	1985	1990
100	0.4	0.4	0.5	0.8	0.4	0.7	0.9	1.4
50	0.6	0.8	0.9	1.4	0.8	1.1	1.6	2.4
25	0.9	1.0	1.2	1.8	1.0	1.5	2.1	3.2
10	1.1	1.4	1.6	2.3	1.3	1.9	2.7	4.0
8	1.2	1.4	1.7	2.5	1.4	2.0	2.8	4.3
6	1.2	1.5	1.8	2.6	1.5	2.2	2.9	4.5
5	1.3	1.6	1.8	2.7	1.5	2.2	3.0	4.7
4	1.3	1.6	1.9	2.8	1.6	2.4	3.1	4.9
3	1.4	1.7	2.0	3.0	1.7	2.5	3.2	5.1
2	1.5	1.8	2.2	3.2	1.8	2.6	3.4	5.3
1	1.6	2.0	2.4	3.4	2.0	2.8	3.6	5.9

b) High diesel exhaust emission rate case

Population exposed millions	Exposure level - $ng/m^3 \times 10^{-3}$							
	Best estimate growth case				Max. growth case			
	1981	1983	1985	1990	1981	1983	1985	1990
100	1.0	2.5	2.9	4.6	2.4	3.7	5.3	8.4
50	1.7	4.3	4.9	7.6	4.1	6.2	8.9	13.8
25	2.3	5.6	6.6	10.0	5.5	8.4	11.8	18.4
10	3.1	7.4	8.6	13.2	7.1	10.9	15.4	23.7
8	3.3	7.7	9.1	13.7	7.5	11.6	16.1	25.0
6	3.5	8.2	9.7	14.5	7.9	12.3	16.9	26.5
5	3.6	8.5	10.2	15.1	8.2	12.8	17.6	27.3
4	3.8	8.9	10.6	16.0	8.4	13.4	18.0	28.2
3	4.0	9.2	11.3	16.7	8.9	14.0	19.2	30.0
2	4.3	9.7	12.2	17.8	9.3	15.0	19.9	32.2
1	4.8	10.4	13.0	19.0	10.0	16.3	21.9	34.5

hour and 1-hour TSP concentrations and maximum annual, 24-hour, and 1-hour concentrations expected to occur near roadways. The corresponding BaP concentrations are determined by applying a ratio of BaP to particulate emissions in calculations for each projection year (presented in Table 4-13).

5.2.1 Estimate of Maximum TSP Impact

The maximum annual TSP concentration from diesel-powered vehicles in 1974 was 0.35 $\mu g/m^3$, occurring in the immediate downtown area. This rather low maximum concentration suggests that diesels contributed a relatively small amount of particulate matter in that year.

The emission data presented earlier, however, indicate that TSP concentrations attributable to diesels will increase through 1990. Table 5-11 summarizes the predicted changes in maximum concentrations over the projection period. Regional annual mean TSP levels, taken from Table 4-13, are also presented.

Maximum 24-hour concentrations can be calculated by application of Larsen's statistical transform.[4] This technique expresses air pollutant concentrations as a function of averaging time and frequency, and it assumes that the following characteristics hold true for any given data set under consideration:

Table 5-11. PROJECTED CONCENTRATIONS OF TSP FROM DIESEL EXHAUST

(μg/m^3)

	1974	1981		1983		1985		1990	
		Best est.	Max.	Best est.	Max.	Best est.	Max.	Best est.	Max.
Regional annual geometric mean	0.35	0.45	0.56	0.57	0.83	0.65	1.13	0.96	1.73
Regional 24-hour maximum	1.05	1.34	1.66	1.68	2.46	1.93	3.38	2.86	5.16
Roadside annual geometric mean	3.85	4.95	6.16	6.27	9.13	7.15	12.43	10.56	19.03
Roadside 24-hour maximum	11.48	14.76	18.36	18.69	27.22	21.31	37.05	31.48	56.73

- pollutant concentrations are lognormally distributed for all averaging times; and
- median concentrations are proportional to averaging time raised to an exponent.

Given these assumptions, Larsen's model may be expressed as:

$$C_{max} = M_g(S_g)^z$$

where C_{max} = the maximum concentration expected for the time period of concern (24 hours for TSP)

M_g = annual geometric mean

S_g = standard geometric deviation

z = an empirical value representing the number of standard deviations from the geometric mean that corresponds to the desired averaging period (or, in other words, to the desired percentile on a normal probability curve)

The numerical value for z, obtainable from any standard statistical text, is 2.94 for a 24-hour period and 3.81 for a 1-hour period. The value for S_g is derived from the standard geometric deviations at the 18 Kansas City sampling sites, which range from 1.29 to 1.69 and average of 1.45.[5] The average value is used in the Larsen computations.

The maximum regional 24-hour concentrations predicted by this technique are presented in Table 5-11. The 1974 maximum is 1.05 $\mu g/m^3$, and the predicted maximum in 1990 is either 2.86 or 5.16 $\mu g/m^3$. Again these values are relatively low; 5.16 $\mu g/m^3$ constitutes 3.4 percent of the 24-hour secondary NAAQS.

A critical limitation of any regional dispersion model is that it predicts concentrations representative of average conditions over relatively large geographical areas. In application of the test city AQDM, predicted values can be regarded as representative of areas 2 km by 2 km square. Other investigations, however, demonstrate clearly that particulate concentrations are not uniform over such areas; rather, they vary considerably according to distance from roadway and elevation above ground.[6,7]

In examining annual mean TSP concentrations at several stations, Record[8] has found that the portion of the average TSP concentration attributable to a nearby roadway can be described by the following empirical expression:

$$C = (T/r)\ (0.265\sin^2\theta + 0.07\cos^2\theta)$$

where C = average contribution of paved road to measured TSP, $\mu g/m^{-3}$
T = average daily traffic, vehicles/day
r = slant distance between monitor and roadway, ft
$\theta = \arctan(z/x)$
z = sampler height, ft
x = horizontal distance between roadway and monitor, ft

Ludwig et al. used this expression to generate the set of curves shown in Figure 4-4, which relate the measured TSP concentrations to the ratio of average daily traffic (ADT) to height and setback of high volume samplers (T/r).[9]

On the basis of 1) the assumption that emissions due to tire wear, vehicle exhaust, and reentrained dust share the same dispersion characteristics, 2) the calculation that roadway-impacted high-volume samplers in the test city are an average of 7 meters above ground and 31 meters from roadways with 17,000 ADT, and 3) the data presented in Figure 4-4, it is estimated that a concentration measured 3 meters above ground and 4 meters from a roadway with 25,000 ADT would exceed a regionally representative concentration by a factor of approximately 11. This value is an approximation that depends heavily upon the assumptions concerning existing samplers. The true factor applicable to the test city probably lies somewhere between 5 and 15.

Application of this estimated roadside adjustment factor yields a maximum annual TSP concentration of 3.85 $\mu g/m^3$ attributable to diesels in 1974. As shown in Table 5-11, the maximum annual concentration is projected to reach 10.56 or 19.03 $\mu g/m^3$ by 1990 depending upon the assumption concerning rate of introduction of diesel vehicles. Maximum 24-hour concentrations near roadways are calculated in a similar fashion. The estimated concentration rises from 11.48 $\mu g/m^3$ in 1974 to 31.48 or 56.73 $\mu g/m^3$ in 1990.

The TSP concentrations projected to be contributed by diesels near roadways in 1990 are not trivial. Calculations with the maximum introduction rate yield concentrations that are 25.3 and 37.8 percent of the primary and secondary NAAQS, respectively.

5.2.2 Estimate of Maximum BaP Impact

BaP concentrations attributable to diesels are projected in a manner identical to that described for TSP, except that BaP concentrations are indirectly modeled by AQDM. It is assumed that a ratio of BaP to particulate emissions can be applied to predicted TSP concentrations to yield predicted BaP concentrations for each grid in a given year. The ratio changes from year to year because of variations in emission factors and vehicle category mix.

The rates in Table 5-12, are calculated by defining the VMT/yr (see Table 4-8), the particulate emission factor, and the BaP emission factor for each diesel vehicle category. Two BaP emission factors are used for each diesel type to correspond with the factors given in Table 4-10. The data are combined and totaled to yield total particulate and BaP emissions from diesels, and ratios between the two totals are developed. The process is repeated for each projection year.

5.3 DISCUSSING EXPOSURE DATA

The assessment of diesel exhaust particulate contribution to ambient exposures of TSP and BaP includes national annual exposure estimates and regional short-term and annual exposure estimates of the most exposed group. Projections of the national exposure distributions indicate that diesel

Table 5-12. PROJECTED MAXIMUM CONCENTRATIONS OF BaP FROM DIESELS

	1974	1981		1983		1985		1990	
		Best est.	Max.	Best est.	Max.	Best est.	Max.	Best est.	Max.
Benzo-a-pyrene (low emission factor), ng/m^3 x 10^{-3}									
Regional annual geometric mean	0.8	1.0	1.2	1.3	1.8	1.4	2.4	2.1	3.7
Regional 24-hour maximum	2.4	3.0	3.7	3.8	5.4	4.2	7.3	6.3	11.1
Regional 1-hour maximum	3.3	4.1	4.9	5.4	7.4	5.8	9.9	8.7	15.2
Roadside annual geometric mean	8.9	11.2	13.6	13.9	19.8	15.6	26.9	23.1	41.0
Roadside 24-hour maximum	26.6	33.5	40.7	41.3	59.0	46.6	80.0	68.9	122.3
Roadside 1-hour maximum	36.7	46.1	56.0	57.3	81.6	64.3	110.8	95.2	168.9
Benzo-a-pyrene$_3$(high emission factor), ng/m x 10^{-3}									
Regional annual geometric mean	4.3	5.5	6.8	6.9	10.1	7.9	13.8	11.7	21.1
Regional 24-hour maximum	12.9	16.5	20.3	20.6	29.9	23.5	41.0	34.8	62.8
Regional 1-hour maximum	17.7	22.7	28.0	28.4	41.6	32.5	56.8	48.2	86.9
Roadside annual geometric mean	147.6	60.7	74.8	76.0	110.6	86.8	151.4	128.4	231.6
Roadside 24-hour maximum	142.0	181.0	273.0	226.6	329.5	258.7	451.2	382.7	690.3
Roadside 1-hour maximum	196.1	250.0	308.1	313.1	455.6	357.5	623.6	528.9	954.0

exhaust will constitute a relatively minor source of TSP and BaP. Diesel vehicles are projected, however, to increase by 1.0 to 2.2 million the total population (over 70 million) exposed to more than the primary annual TSP limit set by standards. The diesel contribution to ambient BaP exposure was found to be quite small. Neither national nor regional estimating procedures are adequately refined to provide a sensitive estimate of the levels of TSP and BaP to which the most exposed segments of the population will be subjected. Such a refinement would require a demographic data base of populated residential areas relative to major roadways and rough-estimate time-and-motion studies. The maximum impact of diesel vehicle emissions near roadways does show the anticipated peak exposures, although no population estimates could be made. A regional 24-hour maximum TSP exposure for the maximum 1990 diesel growth case was only 5 $\mu g/m^3$; however, the maximum exposure case defined as a roadside location resulted in 56.7 $\mu g/m^3$ 24-hour exposure and a 19 $\mu g/m^3$ annual geometric mean exposure (25% of the primary NAAQS). Similar BaP exposure estimates for 1990 resulted in a roadside 24-hour maximum of 0.07 to 0.69 ng/m^3 and an annual geometric mean of 0.02 to 0.23 ng/m^3. Thus, it appears that diesel vehicles are a potentially significant source of TSP and BaP.

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APPENDIX A

Table A-1. FRACTIONS OF LIGHT-DUTY VEHICLE VMT IN PROJECTION YEARS

	Fraction of light duty vehicle VMT								
	1974	1981		1983		1985		1990	
		Best est.	Max.	Best est.	Max.	Best est.	Max.	Best est.	Max.
Diesel vehicles									
Age, years 1	0.0005	0.0068	0.0169	0.0112	0.0281	0.0112	0.0281	0.0112	0.0281
2	0.0008	0.0057	0.0143	0.0115	0.0287	0.0143	0.0359	0.0143	0.0359
3	0.0006	0.0025	0.0066	0.0078	0.0196	0.0130	0.0326	0.0130	0.0326
4	0.0006	0.0006	0.0006	0.0048	0.0121	0.0096	0.0242	0.0121	0.0302
5	0.0005	0.0005	0.0005	0.0021	0.0054	0.0064	0.0163	0.0108	0.0270
6	0.0005	0.0005	0.0005	0.0005	0.0005	0.0037	0.0094	0.0094	0.0236
7	0.0003	0.0003	0.0003	0.0003	0.0003	0.0017	0.0039	0.0079	0.0198
8	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0063	0.0157
9	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0037	0.0095
10	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0019	0.0049
11	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0008	0.0019
12	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0003	0.0007
>13	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Total	0.005	0.0181	0.0409	0.0394	0.0959	0.0611	0.1516	0.0919	0.2301
Gasoline vehicles									
Age, years 1	0.1115	0.1052	0.0951	0.1008	0.0839	0.1008	0.0839	0.1008	0.0839
2	0.1422	0.1373	0.1287	0.1315	0.1143	0.1287	0.1071	0.1287	0.1071
3	0.1294	0.1275	0.1234	0.1222	0.1104	0.1170	0.0974	0.1170	0.0974
4	0.1204	0.1204	0.1204	0.1126	0.1089	0.1114	0.0989	0.1089	0.0908
5	0.1075	0.1075	0.1075	0.1059	0.1026	0.1016	0.0917	0.0972	0.0810
6	0.0935	0.0935	0.0935	0.0935	0.0935	0.0903	0.0846	0.0846	0.0704
7	0.0787	0.0787	0.0787	0.0787	0.0787	0.0773	0.0751	0.0711	0.0592
8	0.0627	0.0627	0.0627	0.0627	0.0627	0.0627	0.0627	0.0567	0.0473
9	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0433	0.0375
10	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0301	0.0271
11	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0182	0.0171
12	0.0129	0.0129	0.0129	0.0129	0.0129	0.0129	0.0129	0.0127	0.0123
>13	0.0388	0.0388	0.0388	0.0388	0.0388	0.0388	0.0388	0.0388	0.0388
Total	0.995	0.9819	0.9591	0.9606	0.9041	0.9389	0.8484	0.9081	0.7699

Table A-2. FRACTIONS OF LIGHT-DUTY TRUCKS VMT IN PROJECTION YEARS

	Fraction of light duty truck VMT								
	1974	1981		1983		1985		1990	
		Best est.	Max.	Best est.	Max.	Best est.	Max.	Best est.	Max.
Diesel trucks									
Age, years 1	0.0005	0.0057	0.0141	0.0094	0.0235	0.0194	0.0235	0.0094	0.0235
2	0.0008	0.0055	0.0138	0.0110	0.0276	0.0138	0.0346	0.0138	0.0346
3	0.0007	0.0026	0.0064	0.0076	0.0191	0.0129	0.0319	0.0129	0.0319
4	0.0007	0.0007	0.0007	0.0052	0.0131	0.0104	0.0261	0.0131	0.0327
5	0.0005	0.0005	0.0005	0.0020	0.0049	0.0059	0.0137	0.0098	0.0246
6	0.0005	0.0005	0.0005	0.0005	0.0005	0.0033	0.0083	0.0083	0.0208
7	0.0004	0.0004	0.0004	0.0004	0.0004	0.0015	0.0038	0.0076	0.0190
8	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0057	0.0144
9	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0036	0.0089
10	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0019	0.0047
11	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0009	0.0023
12	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0003	0.0008
>13	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Total	0.0055	0.0173	0.0378	0.0375	0.0905	0.0586	0.1433	0.0877	0.2186
Gasoline trucks									
Age, years 1	0.0935	0.0883	0.0799	0.0846	0.0705	0.0846	0.0705	0.0846	0.0705
2	0.1372	0.1325	0.1242	0.1270	0.1104	0.1242	0.1034	0.1242	0.1034
3	0.1263	0.1244	0.1206	0.1194	0.1097	0.1141	0.0951	0.1141	0.0951
4	0.1303	0.1303	0.1303	0.1258	0.1179	0.1206	0.1049	0.1179	0.0983
5	0.0975	0.0975	0.0975	0.0960	0.0931	0.0921	0.0843	0.0882	0.0734
6	0.0825	0.0825	0.0825	0.0825	0.0825	0.0797	0.0747	0.0747	0.0622
7	0.0756	0.0756	0.0756	0.0756	0.0756	0.0745	0.0722	0.0684	0.0570
8	0.0567	0.0567	0.0567	0.0567	0.0567	0.0567	0.0567	0.0513	0.0426
9	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0404	0.0351
10	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0301	0.0273
11	0.0229	0.0229	0.0229	0.0229	0.0229	0.0229	0.0229	0.0221	0.0207
12	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159	0.0157	0.0152
>13	0.0806	0.0806	0.0806	0.0806	0.0806	0.0806	0.0806	0.0806	0.0806
Total	0.9945	0.9827	0.9622	0.9625	0.9095	0.9414	0.8567	0.9123	0.7814

Table A-3. FRACTIONS OF HEAVY-DUTY TRUCK VMT FOR PROJECTION YEARS, URBAN ONLY

	Fraction of heavy duty vehicles VMT, urban only								
	1974	1981		1983		1985		1990	
		Best est.	Max.	Best est.	Max.	Best est.	Max.	Best est.	Max.
Gasoline vehicles									
Age, years 1	0.036	0.034	0.029	0.034	0.019	0.032	0.009	0.015	0.0004
2	0.065	0.060	0.053	0.060	0.042	0.059	0.025	0.032	0.004
3	0.068	0.064	0.057	0.064	0.052	0.063	0.034	0.039	0.006
4	0.071	0.068	0.061	0.066	0.056	0.066	0.042	0.046	0.010
5	0.054	0.053	0.051	0.051	0.043	0.050	0.037	0.039	0.009
6	0.047	0.046	0.044	0.044	0.038	0.043	0.033	0.037	0.010
7	0.039	0.038	0.037	0.038	0.035	0.036	0.028	0.032	0.012
8	0.033	0.033	0.031	0.032	0.030	0.031	0.025	0.027	0.013
9	0.027	0.026	0.026	0.026	0.025	0.026	0.022	0.022	0.013
10	0.024	0.023	0.022	0.023	0.021	0.023	0.020	0.019	0.013
11	0.018	0.018	0.017	0.017	0.016	0.017	0.015	0.015	0.011
12	0.012	0.012	0.012	0.012	0.011	0.012	0.010	0.010	0.008
>13	0.089	0.088	0.085	0.087	0.081	0.086	0.074	0.077	0.061
Total	0.583	0.563	0.525	0.554	0.469	0.544	0.374	0.410	0.157
Diesel vehicles									
Age, years 1	0.041	0.045	0.055	0.044	0.075	0.048	0.092	0.078	0.099
2	0.070	0.077	0.090	0.077	0.109	0.076	0.140	0.128	0.163
3	0.070	0.077	0.086	0.077	0.090	0.076	0.120	0.114	0.155
4	0.070	0.073	0.083	0.077	0.086	0.076	0.099	0.096	0.144
5	0.047	0.047	0.045	0.050	0.053	0.049	0.054	0.057	0.092
6	0.032	0.032	0.031	0.035	0.037	0.037	0.037	0.033	0.064
7	0.027	0.027	0.026	0.026	0.025	0.031	0.029	0.028	0.046
8	0.020	0.020	0.019	0.020	0.018	0.022	0.021	0.020	0.028
9	0.015	0.015	0.014	0.015	0.013	0.014	0.012	0.013	0.017
10	0.007	0.007	0.007	0.007	0.006	0.007	0.006	0.008	0.007
11	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
12	0.003	0.003	0.003	0.003	0.003	0.003	0.002	0.003	0.003
>13	0.012	0.012	0.011	0.012	0.011	0.011	0.010	0.010	0.008
Total	0.417	0.437	0.475	0.446	0.531	0.456	0.626	0.590	0.843

APPENDIX B

The TSP levels shown in Table B-1 represent the mean of annual geometric average TSP levels for all ambient monitoring stations reporting in each SMSA shown for the case year.

Table B-1. AVERAGE SMSA TSP LEVELS CORRELATED WITH POPULATION PARAMETERS

SMSA population range, x 10^6	City - State	SMSA population, x 10^6	Urban density, x 10^3/mi^2	TSP $\bar{X}$, mg/m^3	No. of monitoring stations	Year
<0.5	Topeka, KS	0.16	2.5	60.0	7	1976
	Roanoke, VA	0.18	2.4	47.0	11	1975
	South Bend, IN	0.28	2.8	55.4	7	1976
	Evansville, IN	0.23	3.5	66.2	9	1976
	Terre Haute, IN	0.18	2.5	74.6	8	1976
	Anderson, IN	0.14	1.9	55.0	6	1976
	Rockford, IL	0.27	3.4	48.0	4	1975
	Joliet, IL	0.16	2.8	77.0	8	1975
	Saginaw, MI	0.22	3.4	55.0	8	1976
	Green Bay, WI	0.16	1.7	54.8	5	1976
	Charlotte, NC	0.41	2.6	51.0	12	1975
	Winston-Salem, NC	0.3	2.2	62.6	8	1975
	Tulsa, OK	0.48	2.1	69.6	11	1976
	Austin, TX	0.30	3.1	67.4	7	1975
	Billings, MT	0.09	2.6	46.8	5	1976
	Sioux Falls, SD	0.10	2.8	55.5	4	1976
	Spokane, WA	0.29	2.9	74.8	5	1976
	Tacoma, WA	0.41	2.6	46.8	8	1976
	Lancaster, PA	0.32	3.0	60.6	7	1976
	Columbia, SC	0.32	2.3	46.2	6	1975
	Greenville, SC	0.30	2.2	44.4	8	1975
	Chattanooga, TN	0.31	1.9	54.2	11	1975
	Knoxville, TN	0.40	2.2	65.0	6	1975
	Lincoln, NE	0.17	3.0	63.4	8	1976
	Des Moines, IA	0.29	2.3	86.4	5	1976

(continued)

Table B-1 (continued)

SMSA population range, x 10^6	City - State	SMSA population, x 10^6	Urban density, x 10^3/mi^2	TSP $\bar{X}$, mg/m^3	No. of monitoring stations	Year
<0.5	Lexington, KY	0.17	4.0	38.3	4	1975
	Owensboro, KY	0.08	4.4	73.3	6	1975
	Worchester, MA	0.35	2.9	57.6	5	1975
	Flint, MI	~0.5	3.4	54.6	11	1976
	Duluth, MN	0.27	1.2	53.3	8	1976
	Schenectacty, NY	0.20	2.0	46.5	7	1974
0.5-1.0	Albany, NY	0.72	3.2	66.3	6	1974
	Akron, OH	0.68	2.7	64.8	5	1976
	Toledo, OH	0.69	2.9	69.3	9	1976
	Columbus, OH	0.92	3.4	80.1	10	1976
	San Antonio, TX	0.86	3.5	50.7	10	1974
	Omaha, NE	0.54	3.3	75.3	13	1976
	Providence, RI	0.91	3.3	59.0	6	1975
	Norfolk-Portsmouth, VA	0.68	2.2	60.0	4	1975
	Louisville, KY	0.83	3.5	67.4	8	1975
	Grand Rapids, MI	0.54	2.4	50.5	8	1976
	Oklahoma City, OK	0.64	1.7	76.7	26	1976

Summary

Population density range	1	2	3	4
Mean $\bar{X}$	54.3	60.0	59.3	55.8
σ	0.8	12.8	7.1	24.8
No. of SMSA's	4	18	7	2
Total	31			

(continued)

Table B-1 (continued)

SMSA population range, x 10^6	City - State	SMSA population, x 10^6	Urban density, x 10^3/mi^2	TSP $\bar{X}$, mg/m^3	No. of monitoring stations	Year
0.5-1.0	Salt Lake City, UT	0.56	2.6	62.3	7	1976
	Nashville, TN	0.54	1.3	59.2	17	1975
	Richmond, VA	0.52	2.9	58.7	11	1975
	Rochester, NY	0.88	4.1	54.4	7	1974
	Syracuse, NY	0.64	3.9	72.7	9	1973

Summary

Population density range	1	2	3	4
Mean $\bar{X}$	68.0	60.9	64.8	54.4
σ	12.4	6.3	11.9	0
No. of SMSA's	1	6	8	1
Total	15			

1.0-1.5	Buffalo, NY	1.35	5.1	78.5	8	1974
	Denver, CO	1.23	3.6	87.6	7	1976
	Portland, OR	1.01	3.1	50.2	11	1976
	Seattle-Everett, WA	1.42	3.0	63.6	9	1976
	Kansas City, KS	1.25	2.2	63.6	11	1974
	Atlanta, GA	1.39	2.7	53.4	12	1975
	Indianapolis, IN	1.11	2.2	70.6	16	1975
	New Orleans, LA	1.05	11.5	56.4	9	1976

(continued)

Table B-1 (continued)

SMSA population range, x 10^6	City - State	SMSA population, x 10^6	Urban density, x 10^3/mi^2	TSP $\bar{X}_3$, mg/m^3	No. of monitoring stations	Year
1.0-1.5	Milwaukee, WI	1.40	2.7	64.3	24	1975

Summary

Population density range	1	2	3	4
Mean $\bar{X}$	-	63.0	67.1	67.5
σ	-	7.1	18.9	15.6
No. of SMSA's	0	4	3	2
Total	9			

>1.5	Dallas, TX	1.56	2.0	53.4	16	1974
	Houston, TX	1.99	3.1	84.1	8	1974
	Chicago, IL	7.0	5.3	81.0	23	1975
	Philadelphia, PA	4.82	5.3	86.0	12	1976
	Baltimore, MD	2.07	5.1	83.2	10	1976
	Detroit, MI	5.2	4.6	76.8	8	1976
	Minneapolis, MN	1.81	2.4	64.1	18	1976
	Cleveland, OH	2.06	3.0	96.6	25	1976
	St. Louis, MO	2.36	4.1	77.8	20	1976
	New York, NY	9.00	5.3	73.3	25	1976
	Boston, MA	2.76	4.0	51.3	20	1976

Summary

Population density range	1	2	3	4
Mean $\bar{X}$	-	58.8	89.8	75.6
σ	-	7.6	8.1	11.5
No. of SMSA's	0	2	2	7
Total	11			